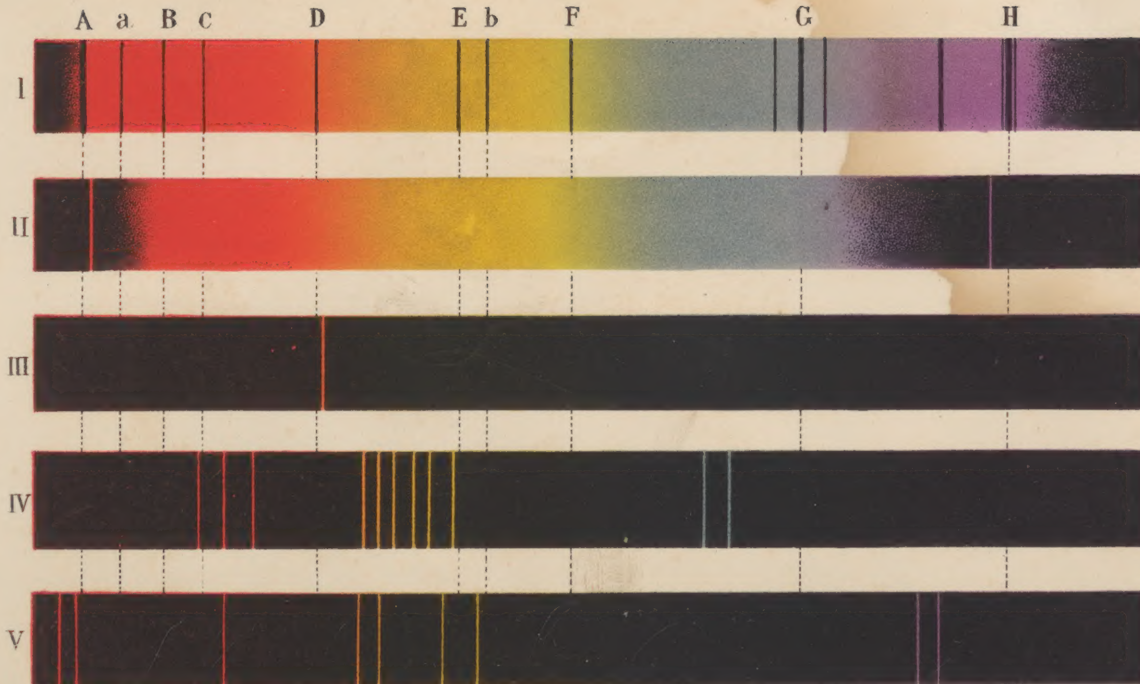

Page 505.

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ELEMENTARY TREATISE

ON

PHYSICS

EXPERIMENTAL AND APPLIED.

FOR THE USE OF COLLEGES AND SCHOOLS.

TRANSLATED AND EDITED FROM

GANOT'S ÉLÉMENTS DE PHYSIQUE

(*with the Author's sanction*)

To replace
8560

(BY Ganot)

E. ATKINSON, PH.D., F.C.S.

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Fifth Edition, Revised and Enlarged.

ILLUSTRATED BY A COLOURED PLATE AND 726 WOODCUTS.

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1872.

ADVERTISEMENT

TO

THE FIFTH EDITION.

In the present edition a somewhat larger and more elegant type and a larger page have been adopted. Thus, while adding twenty-eight new illustrations, and a considerable quantity of new matter, the actual number of pages has been diminished and the book has thereby been rendered more convenient.

In making the additions, while the wants of the general reader have been attended to, the principal aim of the Editor has been, as in former editions, to render the book more useful for the student of physical science. Accordingly, as regards new matter, the main additions have been in those subjects which are calculated to take a permanent place in elementary instruction.

STAFF COLLEGE: *November* 1871.

TRANSLATOR'S PREFACE

TO

THE FIRST EDITION.

THE *Éléments de Physique* of Professor GANOT, of which the present work is a translation, has acquired a high reputation as an Introduction to Physical Science. In France it has passed through Nine large editions in little more than as many years, and it has been translated into German and Spanish.

This reputation it doubtless owes to the clearness and conciseness with which the principal physical laws and phenomena are explained, to its methodical arrangement, and to the excellence of its illustrations. In undertaking a translation, I was influenced by the favourable opinion which a previous use of it in teaching had enabled me to form.

I found that its principal defect consisted in its too close adaptation to the French systems of instruction, and accordingly, my chief labour, beyond that of mere translation, has been expended in making such alterations and additions as might render it more useful to the English student.

I have retained throughout the use of the centrigrade thermometer, and in some cases have expressed the smaller linear measures on the metrical system. These systems are now everywhere gaining ground, and an apology is scarcely needed for an innovation which may help to familiarise the English student with their use in the perusal of the larger and more complete works on Physical Science to which this work may serve as an introduction.

E. ATKINSON.

ROYAL MILITARY COLLEGE, SANDHURST.

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ELEMENTARY TREATISE

ON

PHYSICS.

BOOK I.

ON MATTER, FORCE, AND MOTION.

CHAPTER I.

GENERAL NOTIONS.

1. **Object of Physics.**—The object of *Physics* is the study of the phenomena presented to us by bodies. It should, however, be added, that changes in the nature of the body itself, such as the decomposition of one body into others, are phenomena whose study forms the more immediate object of *chemistry*.

2. **Matter.**—That which possesses the properties whose existence is revealed to us by our senses, we call *matter* or *substance*.

All substances at present known to us may be considered as chemical combinations of sixty-five elementary or *simple* substances. This number, however, may hereafter be diminished or increased by a more powerful chemical analysis.

3. **Atoms, Molecules.**—From various properties of bodies we conclude that the matter of which they are formed is not perfectly continuous, but consists of an aggregate of an immense number of exceedingly small portions or *atoms* of matter. These atoms cannot be divided physically, they are retained side by side, without touching each other, by means of certain attractions and repulsions, to which the name *molecular forces* is given.

A group of atoms forms a *molecule*, so that a body may be considered as an aggregate of very small molecules, and these again as aggregates of still smaller atoms.

From considerations based upon various physical phenomena Sir W. Thomson has calculated that in ordinary solids and liquids the average

distance between contiguous molecules is less than the hundred millionth and greater than the two thousand millionth of a centimetre.

To give an idea of the degree of the size of the molecules Sir W. Thomson gives this illustration : 'Imagine a drop of rain, or a glass sphere the size of a pea, magnified to the size of the earth, the molecules in it being increased in the same proportion. The structure of the mass would then be coarser than that of a heap of fine shot, but probably not so coarse as that of a heap of cricket-balls.'

4. **Molecular state of bodies.**—With respect to the molecules of bodies three different states of aggregation present themselves.

First, the solid state, as observed in woods, stones, metals, etc., at the ordinary temperature. The distinctive character of this state is, that the relative positions of the molecules of the bodies cannot be changed without the expenditure of more or less force. As a consequence, solid bodies tend to retain whatever form may have been given to them by nature or by art.

Secondly, the liquid state, as observed in water, alcohol, oil, etc. Here the relative position of the molecules is no longer permanent, the molecules glide past each other with the greatest ease, and the body assumes with readiness the form of any vessel in which it may be placed.

Thirdly, the gaseous state, as in air. In gases the mobility of the molecules is still greater than in liquids ; but the distinctive character of a gas is its incessant struggle to occupy a greater volume, or the tendency of its molecules to recede from each other.

The general term *fluid* is applied to both liquids and gases.

We shall see in the sequel that the state of a body depends upon the relations which exist between its molecular attractions and repulsions, and that for one and the same body these relations vary with the temperature. On this account most simple bodies, and many compound ones, may be made to pass successively through all the three states. Water presents the most familiar example of this.

5. **Physical phenomena, laws, and theories.**- Every change which can happen to a body, mere alteration of its chemical constitution being excepted, may be regarded as a *physical phenomenon*. The fall of a stone, the vibration of a string, and the sound which accompanies it, the rippling of the surface of a lake, and the freezing of water, are examples of such phenomena.

A *physical law* is the constant relation which exists between any phenomenon and its cause. As an example, we have the phenomenon of the diminution of the volume of a gas by the application of pressure ; the corresponding law has been determined, and is expressed by saying that the volume of a gas is inversely proportional to the pressure.

The whole of the laws referring to the same class of phenomena, taken together, constitute a *physical theory*. Thus we have the theory of light, the theory of electricity, and, in more restricted forms, the theory of dew, and the theory of the mirage.

6. **Physical agents.**—In our attempts to ascend from a phenomenon to its cause, we assume the existence of *physical agents*, or *natural forces*,

acting upon matter; as examples of such we have *gravitation*, *heat*, *light*, *magnetism*, and *electricity*.

Since these physical agents are disclosed to us only by their effects, their intimate nature is completely unknown. In the present state of science, we cannot say whether they are properties inherent in matter, or whether they result from movements impressed on the mass of subtile and imponderable forms of matter diffused through the universe. The latter hypothesis is however generally admitted. This being so it may be further asked are there several distinct forms of imponderable matter, or are they in reality but one and the same? It would seem that the latter opinion tends to prevail as the physical sciences extend their limits. In accordance with this hypothesis these subtile forms of matter are spoken of as *imponderable fluids*, since their weight is inappreciable by the aid of the most delicate balances. Hence arises the distinction sometimes made between *ponderable matter*, or matter properly so called, and *imponderable matter*, or physical agents.

The term *incoercible* is also applied to these imponderable fluids, to express the impossibility of confining them in, or excluding them from, any closed vessel, as we do air and other gases.

CHAPTER II.

GENERAL PROPERTIES OF BODIES.

7. **Different kinds of properties.**—By the term *properties* as applied to bodies, we understand the different ways in which bodies present themselves to our senses. We distinguish *general* from *specific* properties. The former are shared by all bodies, and amongst them the most important are *impenetrability*, *extension*, *divisibility*, *porosity*, *compressibility*, *elasticity*, *mobility*, and *inertia*.

Specific properties are such as are observed in certain bodies only, or in certain states of those bodies; such are *solidity*, *fluidity*, *tenacity*, *ductility*, *malleability*, *hardness*, *transparency*, *colour*, &c.

With respect to the above general properties, it may be remarked that *impenetrability* and *extension* might be more aptly termed essential attributes of matter, since they suffice to define it; and that divisibility, porosity, compressibility, and elasticity, do not apply to atoms, but only to bodies or aggregates of atoms (3).

8. **Impenetrability.**—*Impenetrability* is the property in virtue of which two portions of matter cannot, at the same time, occupy the same portion of space.

Strictly speaking, this property applies only to the atoms of a body. In many phenomena bodies appear to penetrate each other; thus, the volume of a compound body is always less than the sum of the volumes of its constituents; for instance, the volume of a mixture of water and sulphuric acid, or of water and alcohol, is less than the sum of the volumes

before mixture. In all these cases, however, the penetration is merely apparent, and arises from the fact that in every body there are interstices or spaces unoccupied by matter.

9. **Extension.**—*Extension* or *magnitude* is the property in virtue of which every body occupies a limited portion of space.

Many instruments have been invented for measuring linear extension or lengths with great precision. Two of these, the vernier and micrometer screw, on account of their great utility, deserve to be here mentioned.

10. **Vernier.**—The *vernier* forms a necessary part of all instruments where lengths or angles have to be estimated with precision; it derives its name from its inventor, a French mathematician, who died in 1637, and consists essentially of a short graduated scale, *ab*, which is made to

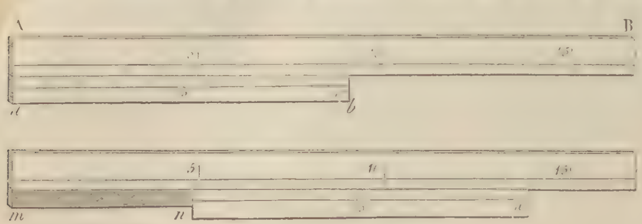


Fig. 1.

slide along a fixed scale, AB, so that the graduations of both may be compared with each other. The fixed scale, AB, being divided into equal parts, the whole length of the vernier, *ab*, may be taken equal to nine of those parts, and itself divided into ten equal parts. Each of the parts of the vernier, *ab*, will then be less than a part of the scale by one tenth of the latter.

This granted, in order to measure the length of any object, *mn*, let us suppose that the latter, when placed as in the figure, has a length greater than four but less than five parts of the fixed scale. In order to determine by what fraction of a part *mn* exceeds four, one of the ends, *a*, of the vernier, *ab*, is placed in contact with one extremity of the object, *mn*, and the division on the vernier is sought which coincides with a division on the scale, AB. In the figure this coincidence occurs at the eighth division of the vernier, counting from the extremity, *n*, and indicates that the fraction to be measured is equal to $\frac{8}{10}$ of a part of the scale, AB. In fact, each of the parts of the vernier being less than a part of the scale by $\frac{1}{10}$ of the latter, it is clear that on proceeding towards the left from the point of coincidence, the divisions of the vernier are respectively one, two, three, etc., tenths behind the divisions of the scale; so that the extremity, *n*, of the object (that is to say, the eighth division of the vernier) is $\frac{8}{10}$ behind the division marked 4 on the scale; in other words, the length of *mn* is equal to $4\frac{8}{10}$ of the parts into which the scale AB is divided. Consequently, if the scale AB were divided into inches, the length of *mn* would be $4\frac{8}{10} = 4\frac{4}{5}$ inches. The divisions on the scale remaining the same, it

would be necessary to increase the length of the vernier in order to measure the length *mn* more accurately. For instance, if the length of the vernier were equal to nineteen of the parts on the scale, and this length were divided into twenty equal parts, the length *mn* could be determined to the twentieth of a part on a scale, and so on. In instruments, like the theodolite, intended for measuring angles, the scale and vernier have a circular form, and the latter usually carries a magnifier, in order to determine with greater precision the coincident divisions of vernier and scale.

11. **Micrometer screw.**—Another useful little instrument for measuring small lengths with precision is the *micrometer screw.* It is used under various forms, but the principle is the same in all, and may be illustrated by a simple example. Suppose the distance between the threads of an accurately cut screw to be equal to $\frac{1}{10}$ of an inch, and the head of the screw to be a tolerably large circle divided into one hundred equal parts. If the screw is fixed in such a manner that it can only turn on its axis, but neither advance nor recede, and if it work in a nut held between guides which prevent it from turning, then every turn of the screw will cause the nut to advance through the tenth part of an inch. If a fixed pointer be placed before the divided circle at the head of the screw, and the latter turned through so small an angle that only one division of the circle passes under the pointer, the hundredth part of a turn will have been given to the screw, and the nut thereby caused to advance or recede through the hundredth part of the distance between two threads – that is to say, through the $\frac{1}{1000}$ part of an inch. Applications of this principle to the measurement of small lengths will at once suggest themselves, and be readily understood when seen.

12. **Divisibility**—is the property in virtue of which a body may be divided into distinct parts.

Numerous examples may be cited of the extreme divisibility of matter. The tenth part of a grain of musk will continue for years to fill a room with its odoriferous particles, and at the end of that time will scarcely be diminished in weight.

Blood is composed of red, flattened globules floating in a colourless liquid called serum. In man the diameter of one of these globules is less than the 3,500th part of an inch, and the drop of blood which might be suspended from the point of a needle would contain about a million of globules.

Again, the microscope has disclosed to us the existence of insects smaller even than these particles of blood; the struggle for existence reaches even to these little creatures, for they devour still smaller ones. If blood runs in the veins of these devoured ones, how infinitesimal must be the magnitude of its component globules?

Has then the divisibility of matter no limit? Although experiment fails to determine such limit, many facts in chemistry, such as the invariability in the relative weights of the elements which combine with each other, would lead us to believe that a limit does exist. It is on this

account that bodies are conceived to be composed of extremely minute and indivisible parts called *atoms* (3).

13. **Porosity.**—*Porosity* is the quality in virtue of which interstices or *pores* exist between the molecules of a body.

Two kinds of pores may be distinguished : *physical pores*, where the interstices are so small that the surrounding molecules remain within the sphere of each other's attracting or repelling forces; and *sensible pores*, or actual cavities across which these molecular forces cannot act. The contractions and dilatations resulting from variations of temperature are due to the existence of physical pores, whilst in the organic world the sensible pores are the seat of the phenomena of exhalation and absorption.

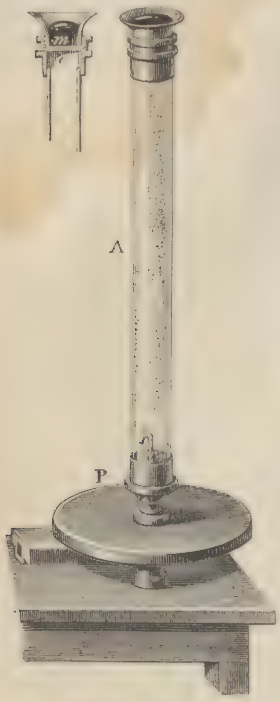


Fig. 2.

In wood, sponge, and a great number of stones, for instance, pumice stone, the sensible pores are apparent ; physical pores never are. Yet, since the volume of every body may be diminished, we conclude that all possess physical pores.

The existence of sensible pores may be shown by the following experiment :—A long glass tube, A (fig. 2), is provided with a brass cup, *m*, at the top, and a brass foot made to screw on to the plate of a machine for exhausting air. The bottom of the cup consists of a thick piece of leather. After pouring mercury into the cup so as entirely to cover the leather, the air-pump is put in action, and a partial vacuum produced within the tube. By so doing a shower of mercury is at once produced within the tube, for the atmospheric pressure on the mercury forces that liquid through the pores of the leather. In the same manner water or mercury may be forced through the pores of wood, by replacing the leather in the above experiment by a disc of wood cut perpendicular to the fibres.

When a piece of chalk is thrown into water air-bubbles at once rise to the surface, in consequence of the air in the pores of the chalk being expelled by the water. The chalk will be found to be heavier after immersion than it was before, and from the increase of its weight the volume of its pores may be easily determined.

The porosity of gold was demonstrated by the celebrated Florentine experiment made in 1661. Some academicians at Florence, wishing to try whether water was compressible, filled a thin globe of gold with that liquid, and, after carefully closing the orifice hermetically, they exposed

the globe to pressure with a view of altering its form, well knowing that any alteration in form must be accompanied by a diminution in volume. The consequence was, that the water forced its way through the pores of the gold, and stood on the outside of the globe like dew. This experiment has since been repeated with globes of other metals, and like results obtained.

14. **Apparent and real volumes.**—In consequence of the porosity of bodies, it becomes necessary to distinguish between their real and apparent volumes. The *real volume* of a body is the portion of space actually occupied by the matter of which the body is composed; its *apparent volume* is the sum of its real volume and the total volume of its pores. The real volume of a body is invariable, but its apparent volume can be altered in various ways.

15. **Applications.**—The property of porosity is utilised in filters of paper, felt, stone, charcoal, etc. The pores of these substances are sufficiently large to allow liquids to pass, but small enough to arrest the passage of any substances which these liquids may hold in suspension. Again, large blocks of stone are often detached in quarries by introducing wedges of dry wood into grooves cut in the rock. These wedges being moistened, water penetrates their pores, and causes them to swell with considerable force. Dry cords, when moistened, increase in diameter and diminish in length, a property of which advantage is sometimes taken in order to raise immense weights.

16. **Compressibility.**—*Compressibility* is the property in virtue of which the volume of a body may be diminished by pressure. This property is at once a consequence and a proof of porosity.

Bodies differ greatly with respect to compressibility. The most compressible bodies are gases; by sufficient pressure they may be made to occupy ten, twenty, or even a hundred times less space than they do under ordinary circumstances. In most cases, however, there is a limit beyond which, when the pressure is increased, they become liquids.

The compressibility of solids is much less than that of gases, and is found in all degrees. Cloths, paper, cork, woods, are amongst the most compressible. Metals are so also to a great extent, as is proved by the process of coining, in which the metal receives the impression from the die. There is, in most cases, a limit beyond which, when the pressure is increased, bodies are fractured or reduced to powder.

The compressibility of liquids is so small as to have remained for a long time undetected: it may, however, be proved by experiment, as will be seen in the chapter on Hydrostatics.

17. **Elasticity.**—*Elasticity* is the property in virtue of which bodies resume their original form or volume, when the force which altered that form or volume ceases to act. Elasticity may be developed in bodies by pressure, traction, flexion, or torsion. In treating of the general properties of bodies, the elasticity developed by pressure alone requires consideration; the other kinds of elasticity being peculiar to solid bodies, will be considered amongst their specific properties (arts. 79, 80, 81).

Gases and liquids are perfectly elastic; in other words, they regain

exactly the same volume when the pressure becomes the same. Solid bodies present different degrees of elasticity, though none present the property in the same perfection as liquids and gases, and in all it varies according to the time during which the body has been exposed to pressure. Caoutchouc, ivory, glass, and marble possess considerable elasticity; lead, clay, and fats, scarcely any.

There is a limit to the elasticity of solids, beyond which they either break or are incapable of regaining their original form and volume. In sprains, for instance, the elasticity of the tendons has been exceeded. In gases and liquids, on the contrary, no such limit can be reached; they always regain their original volume.

If a ball of ivory, glass, or marble, be allowed to fall upon a slab of polished marble, which has been previously slightly smeared with oil, it will rebound and rise to a height nearly equal to that from which it fell. On afterwards examining the ball a circular blot of oil will be found upon it, more or less extensive according to the height of the fall. From this we conclude that at the moment of the shock the ball was flattened, and that its rebound was caused by its effort to regain original form.

18. **Mobility, motion, rest.**—*Mobility* is the property in virtue of which the position of a body in space may be changed.

Motion and rest may be either relative or absolute. By the *relative motion* or *rest* of a body we mean its change or permanence of position with respect to surrounding bodies; by its *absolute motion* or *rest* we mean the change or permanence of its position with respect to ideal fixed points in space.

Thus a passenger in a railway carriage may be in a state of relative rest with respect to the train in which he travels, but he is in a state of relative motion with respect to the objects (fields, houses, etc.) past which the train rushes. These houses again enjoy merely a state of relative rest, for the earth itself which bears them is in a state of incessant relative motion with respect to the celestial bodies of our solar system. In short, absolute motion and rest are unknown to us; in nature, relative motion and rest are alone presented to our observation.

19. **Inertia.**—*Inertia* is a purely negative property of matter; it is the incapability of matter to change its own state of motion or rest.

A body when unsupported in mid-air does not fall to the earth in virtue of any inherent property, but because it is acted upon by the force of gravity. A billiard ball gently pushed does not move more and more slowly, and finally stop, because it has any preference for a state of rest, but because its motion is impeded by the friction on the cloth on which it rolls, and by the resistance of the air. If all impeding causes were withdrawn, a body once in motion would continue to move for ever.

20. **Application.**—Innumerable phenomena may be explained by the inertia of matter. For instance, before leaping a ditch we run towards it, in order that the motion of our bodies at the time of leaping may add itself to the muscular effort then made.

On descending carelessly from a carriage in motion, the upper part of the body retains its motion, whilst the feet are prevented from doing so

by friction against the ground; the consequence is we fall towards the moving carriage.

The terrible accidents on our railways are chiefly due to inertia. When the motion of the engine is suddenly arrested the carriages strive to continue the motion they had acquired, and in doing so are shattered against each other.

Hammers, pestles, stampers are applications of inertia. So are also the enormous iron fly wheels, by which the motion of steam engines is regulated.

CHAPTER III.

ON FORCE, EQUILIBRIUM, AND MOTION.

21. **Measure of Time.**—To obtain a proper measure of force it is necessary, as a preliminary, to define certain conceptions which are presupposed in that measure; and, in the first place, it is necessary to define the unit of time. Whenever a *second* is spoken of without qualification it is understood to be a second of *mean solar time*. The exact length of this unit is fixed by the following consideration. The instant when the sun's centre is on an observer's meridian—in other words, the instant of the transit of the sun's centre—admits of exact determination, and thus the interval which elapses between two successive transits also admits of exact determination, and is called an *apparent* day. The length of this interval differs slightly from day to day, and therefore does not serve as a convenient measure of time. Its *average* length is free from this inconvenience, and therefore serves as the required measure, and is called a *mean solar day*. The short hand of a common clock would go exactly twice round the face in a mean solar day if it went perfectly. The mean solar day consists of 24 equal parts called *hours*, these of 60 equal parts called *minutes*, and these of 60 equal parts called *seconds*. Consequently the second is the 86,400th part of a mean solar day, and is the generally received unit of time.

22. **Measure of Space.**—Space may be either *length* or *distance*, which is space of one dimension; *area*, which is space of two dimensions; or *volume*, which is space of three dimensions. In England the standard of length is the British Imperial Yard, which is the distance between two points on a certain metal rod, kept in the Tower of London, when the temperature of the whole rod is 60° F. = 15°·5 C. It is, however, usual to employ as a unit, a *foot*, which is the third part of a yard. In France the standard of length is the metre; this, too, is practically fixed by the distance between two marks on a certain standard rod. The relation between these standards is as follows:

1 yard = 0·914383 metre.
1 metre = 1·093633 yards.

The unit of length having been fixed, the units of area and volume are

connected with it thus:—the unit of area is the area of a square, one side of which is the unit of length. The unit of volume is the volume of a cube, one edge of which is the unit of length. These units in the case of English measures are the square yard (or foot) and the cubic yard (or foot) respectively; in the case of French measures, the square metre and cubic metre respectively.

23. **Measure of Mass.**—Two bodies are said to have equal masses when, if placed in a perfect balance in vacuo, they counterpoise each other. Suppose we take lumps of any substance, lead, butter, wood, stone, etc., and suppose that any of them when placed on one pan of a balance will exactly counterpoise any other of them when placed on the opposite pan—the balance being perfect and the weighing performed in vacuo; this being the case, these lumps are said to have equal masses. That these lumps differ in many respects from each other is plain enough; in what respects they have the same properties in virtue of the equality of their masses is to be ascertained by subsequent enquiry.

The British unit of mass is the standard pound (avoirdupois), which is a certain piece of platinum kept in the Exchequer Office in London. This unit having been fixed, the mass of a given substance is expressed as a multiple or submultiple of the unit.

It need scarcely be mentioned that many distances are ascertained and expressed in yards which it would be physically impossible to measure directly by a yard measure. In like manner the masses of bodies are frequently ascertained and expressed numerically which could not be placed in a balance and subjected to direct weighing.

24. **Density and Relative Density.**—If we consider any body or portion of matter, and if we conceive it to be divided into any number of parts having equal volumes, then, if the masses of these parts are equal, in whatever way the division be conceived as taking place, that body is one of *uniform density*. The *density* of such a body is the mass of the *unit of volume*. Consequently if M denote the mass, V the volume, and D the density of the body, we have

$$M = VD.$$

If now we have an equal volume V of any second substance whose mass is M' and density D', we shall have

$$M' = VD'.$$

Consequently $D : D' :: M : M'$; that is the densities of substances are in the same ratio as the masses of equal volumes of those substances. If now we take the density of distilled water at 4° C. to be unity, the relative density of any other substance is the ratio which the mass of any given volume of that substance at that temperature bears to the mass of an equal volume of water. Thus it is found that the mass of any volume of platinum is 22·069 times that of an equal volume of water, consequently the relative density of platinum is 22·069.

The relative density of a substance is generally called its *specific gravity*. Methods of determining it are given in Book III.

In French measures the *cubic decimetre* or *litre* of distilled water at 4° C.

contains the unit of mass, the *kilogramme*; and therefore the mass in kilogrammes of V cubic decimetres of a substance whose specific gravity is D, will be given by the equation

$$M = VD.$$

The same equation will give the mass in *grammes* of the body, if V is given in millimetres.

It has been ascertained that 27·7274 cubic inches of distilled water at the temperature 15°·5 C. or 60° F. contain a pound of matter. Consequently, if V is the *volume* of a body in cubic inches, D its *specific gravity*, its mass M in lbs. avoirdupois will be given by the equation

$$M = \frac{VD}{27 \cdot 7274}.$$

In this equation D is, properly speaking, the relative density of the substance at 60° F. when the density of water at 60° F. is taken as the unit.

25. **Velocity and its measure.**—When a material point moves, it describes a continuous line which may be either straight or curved, and is called its *path* and sometimes its *trajectory*. Motion which takes place along a straight line is called *rectilinear* motion; that which takes place along a curved line is called *curvilinear* motion. The rate of the motion of a point is called its *velocity*. Velocity may be either uniform or variable; it is uniform when the point describes equal spaces or portions of its path in all equal times; it is variable when the point describes unequal portions of its path in any equal times.

Uniform velocity is measured by the number of units of space described in a given unit of time. The units commonly employed are feet and seconds. If, for example, a velocity 5 is spoken of without qualification, this means a velocity of 5 feet per second. Consequently, if a body moves for t seconds with a uniform velocity v, it will describe vt feet.

Variable velocity is measured at any instant by the number of units of space it would describe if it continued to move uniformly from that instant for a unit of time. Thus, suppose a body to run down an inclined plane, it is a matter of ordinary observation that it moves more and more quickly during its descent; suppose that at any point it has a velocity 15, this means that at that point it is moving at the rate of 15 ft. per second, or, in other words, if from that point all increase of velocity ceased, it would describe 15 ft. in the next second.

26. **Force.**—When a material point is at rest, it has no innate power of changing its state of rest; when it is in motion it has no innate power of changing its state of uniform motion in a straight line. This property of matter is termed its *inertia*. Any cause which sets a point in motion, or which changes the magnitude or direction of its velocity if in motion, is a *force*. *Gravity*, *friction*, *elasticity* of springs or gases, *electrical* or *magnetic attraction* or *repulsion*, &c. are *forces*. All changes observed in the motion of bodies can be referred to the action of one or more forces.

27. **Accelerative effect of force.**—If we suppose a force to continue unchanged in magnitude, and to act along the line of motion of a point, it will communicate in each successive second a constant increase

of velocity. This constant increase is the *accelerative effect of the force.* Thus if at any given instant the body has a velocity 10, and if at the end of the first, second, third, etc., second from that instant its velocity is 13, 16, 19, etc., the accelerative effect of the force is 3; a fact which is expressed by saying that the body has been acted on by an accelerating force 3.

If the force vary from instant to instant, its accelerative effect will also vary; when this is the case the accelerative effect at any instant is measured by the velocity it would communicate in a second if the force continued constant from that instant.

By means of an experiment to be described below (70) it can be shown that at any given place the accelerative effect of gravity g is constant; but it is found to have different values at different places, adopting the units of feet and seconds it is found that very approximately

$$g = f(1 - 0{\cdot}00256 \cos 2\phi)$$

at a station whose latitude is ϕ, where f denotes the number 32·1724.

28. **Momentum** or quantity of motion is a magnitude varying as the mass of a body and its velocity jointly, and therefore is expressed numerically by the product of the number of units of mass which it contains and the number of units of velocity in its motion. Thus a body containing 5 lbs. of matter, and moving at the rate of 12 ft. per second, has a momentum of 60.

29. **Measure of force.**—Force, when constant, is measured by the *momentum* it communicates to a body in a unit of time. If the force varies, it is then measured at any instant by the momentum it would communicate if it continued constant for a unit of time from the instant under consideration. The unit of force is that force which acting on a pound of matter would produce in one second a velocity of one foot per second. Consequently if a body contains m lbs. of matter, and is acted on by a force whose accelerative effect is f, that force contains a number of units of force (F), given by the equation

$$F = mf.$$

The weight of a body, *when that term denotes a force*, is the force exerted on it by gravity; consequently, if m is the mass of the body, and g the accelerating force of gravity, the number of units of force W exerted on it by gravity is given by the equation

$$W = mg$$

or (27) $$W = mf(1 - 0{\cdot}00256 \cos 2\phi).$$

From this it is plain that the weight of the same body will be different at different parts of the earth's surface; a fact which could be verified by attaching a piece of platinum (or other metal) to a delicate spring, and noting the variations in the length of the spring during a voyage from a station in the Northern Hemisphere to another in the Southern Hemisphere, for instance, from London to the Cape of Good Hope.

When, therefore, a pound is used as a unit of force it must be under-

stood to mean the force W exerted by gravity on a pound of matter in London. Now, in London, the numerical value of g is 32·1912, so that

$$W = 1 \times 32{\cdot}1912;$$

in other words, when a pound is taken as the unit of force it contains 32·1912 units of force according to the measure given above. It will be observed that a pound of matter is a completely determinate quantity of matter, irrespective of locality, but gravity exerts on a pound of matter a pound (or 32·1912 units) of force at London and other places in about the same latitude as London only; this ambiguity in the term *pound* should be carefully noticed by the student; the context in any treatise will always show in which sense the term is used.

30. **Representation of forces.**—Draw any straight line AB, and fix on any point O in it. We may suppose a force to act on the point O, along the line AB, either towards A or B: then O is called the point of application of the force, AB its line of action; if it acts towards A, its *direction* is OA, if towards B, its direction is OB. It is rarely necessary to make the distinction between the line of action and direction of a force; it being very convenient to make the convention that the statement—a force acts on a point O along the line OA—means that it acts from O to A. Let us suppose the force which acts on O along OA to contain P units of force; from O towards A measure ON containing P units of length, the line ON is said to *represent* the force. It will be remarked that the analogy between the line and the force is very complete; the line ON is drawn from O in a given direction OA, and contains a given number of units P, just as the force acts on O in the direction OA, and contains a given number of units P. It is scarcely necessary to add that if an equal force were to act on O in the opposite direction, it would be said to act in the direction OB, and would be represented by OM, equal in magnitude to ON.

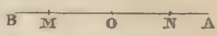


Fig. 3.

When we are considering several forces acting along the same line we may indicate their directions by the positive and negative signs. Thus the forces mentioned above would be denoted by the symbols $+P$ and $-P$ respectively.

31. **Forces acting along the same line.**—If forces act on the point O in the direction OA containing P and Q units respectively, they are equivalent to a single force R containing as many units as P and Q together, that is,

$$R = P + Q$$

If the sign + in the above equation *denote algebraical* addition, the equation will continue true whether one or both of the forces act along OA or OB. It is plain that the same rule can be extended to any number of forces, and if several forces have the same line of action they are equivalent to one force containing the same number of units as their *algebraical* sum. Thus if forces of 3 and 4 units act on O in the direction OA, and a force of 8 in the direction OB, they are equivalent to a single force containing R units given by the equation

$$R = 3 + 4 - 8 = -1;$$

that is, R is a force containing one unit acting along OB. This force R is called their resultant. If the forces are in equilibrium R is equal to zero. In this case the forces have equal tendencies to move the point O in opposite directions.

32. **Resultant and components.**—In the last article we saw that a single force R could be found equivalent to several others; this is by no means peculiar to the case in which all the forces have the same line of action; in fact, when a material point, A (fig. 4), remains in equilibrium under the action of several forces, S, P, Q, it does so because any one of the forces, as S, is capable of neutralising the combined effects of all the others. If the force S, therefore, had its direction reversed, so as to act along AR, the prolongation of AS, it would produce the same effect as the system of forces P, Q.

Fig. 4.

Now, a force whose effect is equivalent to the combined effects of several other forces is called their *resultant*, and with respect to this resultant, the other forces are termed *components*.

When the forces, P, Q, act on a point they can only have *one* resultant; but any single force can be resolved into components in an indefinite number of ways.

If a point move from rest under the action of any number of forces it will begin to move in the direction of their resultant.

33. **Parallelogram of forces.**—When two forces act on a point their resultant is found by the following theorem, known as the principle of the parallelogram of forces :—*If two forces act on a point, and if lines be drawn from that point representing the forces in magnitude and direction, and on these lines as sides a parallelogram be constructed, their resultant will be represented in magnitude and direction by that diagonal which passes through the point.* Thus let P and Q (fig. 5) be two forces acting on the point A along AP and AQ respectively, and let AB and AC be taken containing the same number of units of length that P and Q contain units of force ; let the parallelogram AB DC be completed, and the

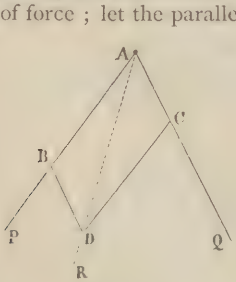


Fig. 5.

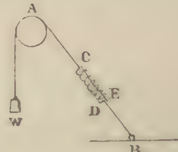


Fig. 6.

diagonal AD drawn ; then the theorem states that the resultant, R, of P and Q is represented by AD ; that is to say, P and Q together are equal

to a single force R acting along the line AD, and containing as many units of force as AD contains units of length.

Proofs of this theorem are given in treatises on Mechanics; we will here give an account of a direct experimental verification of its truth; but before doing so we must premise an account of a very simple experiment.

Let A (fig. 6) be a small pulley, and let it turn on a smooth, hard, and thin axle with little or no friction; let W be a weight tied to the end of a fine thread which passes over the pulley; let a spring CD be attached by one end to the end C of the thread and by the end D to another piece of thread, the other end of which is fastened to a fixed point B; a scale CE can be fastened by one end to the point C and pass inside the spring so that the elongation of the spring can be measured. Now it will be found on trial that with a given weight W the elongation of the spring will be the same whatever the angle contained between the parts of the string WA and BA. Also it would be found that if the whole were suspended from a fixed point, instead of passing over the pulley, the weight would in this case stretch the spring to the same extent as before. This experiment shows that when care is taken to diminish to the utmost the friction of the axle of the pulley, and the imperfect flexibility of the thread, the weight of W is transmitted without sensible diminution to B, and exerts on that point a pull or force along the line BA virtually equal to W.

This being premised, the experimental proof, or illustration of the parallelogram of forces, is as follows:—

Suppose H and K (fig. 7) to be two pulleys with axles made as smooth and fine as possible; let P and Q be two weights suspended from fine and flexible threads which, after passing over H and K, are fastened at A to a third thread AL from which hangs a weight R; let the three weights come to rest in the positions shown in the figure. Now the point A is acted on by three forces in equilibrium, viz., P from A to H, Q from A to K, and R from A to L, consequently, any one of them must be equal and opposite to the resultant of the other two. Now if we suppose the apparatus to be arranged immediately in front of a large slate, we can draw lines upon it coinciding with AH, AK, and AL. If now we measure off along AH the part AB containing as many inches as P contains pounds, and along AK the part AC containing as many inches as Q contains pounds, and complete the parallelogram ABCD, it will be found that the diagonal AD is in the same line as AL, and contains as many inches as R weighs pounds. Consequently, the resultant of P and Q is represented by AD. Of course, any other units of length and force might have been employed. Now it will be found that when P, Q, and R are changed in any way whatever consistent with equilibrium the same construction can be made,—the point A will have different positions in the different cases; but when equilibrium is established, and the parallelogram ABCD is constructed, it will be found that AD is vertical, and

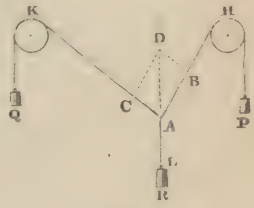


Fig. 7.

contains as many units of length as R contains units of force, and consequently it represents a force equal and opposite to R, that is, it represents the resultant of P and Q.

34. **Resultant of any number of forces acting in one plane on a point.**—Let the forces, P, Q, R, S (fig. 8) act on the point A, and let them be represented by the lines AB, AC, AD, AE, as shown in the figure. *First*, complete the parallelogram AB FC and join AF; this line represents the resultant of P and Q. *Secondly*, complete the parallelogram AFGD and join AG; this line represents the resultant of P, Q, R. *Thirdly*, complete the parallelogram AGHE and join AH; this line represents the resultant of P, Q, R, S. It is manifest that the construction can be extended to any number of forces. A little consideration will show that the line AH might be determined by the following construction:—through B draw BF parallel to, equal to, and towards the same part as AC; through F draw FG parallel to, equal to, and towards the same part as AD; through G draw GH parallel to, equal to, and towards the same part as AE; join AH, then AH represents the required resultant.

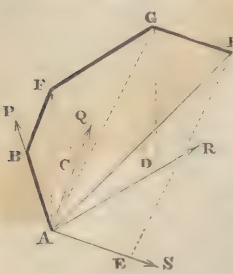


Fig. 8.

In place of the above construction, the resultant can be determined by calculation in the following manner:—Through A draw any two rectangular axes Ax and Ay (fig. 9), and let α, β, γ be the angles made with the axis Ax by the lines representing the pressures, then P, Q, R can be resolved into P cos α, Q cos β, R cos γ, acting along Ax, and P sin α, Q sin β, R sin γ, acting along Ay. Now the former set of forces can be reduced to a single force X by addition, attention being paid to the sign of each component; and in like manner the latter forces can be reduced to a single force Y, that is,

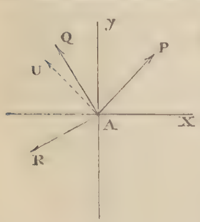


Fig. 9.

$$X = P\cos\alpha + Q\cos\beta + R\cos\gamma + \ldots$$
$$Y = P\sin\alpha + Q\sin\beta + R\sin\gamma + \ldots$$

Since the addition denotes the *algebraical* sum of the quantities on the right hand side of the equations, both *sign* and *magnitude* of X and Y are known. Suppose U to denote the required resultant, and ϕ the angle made by the line representing it with the axis Ax;

then $$U\cos\phi = X, \text{ and } U\sin\phi = Y.$$

These equations give $U^2 = X^2 + Y^2$, which determines the magnitude of the resultant, and then, since both sin ϕ and cos ϕ are known, ϕ is determined without ambiguity.

Thus let P, Q, and R be forces of 100, 150, and 120 units, respectively, and suppose xAP, xAQ, and xAR to be angles of 45°, 120°, and 210° respectively. Then their components along Ax are 70·7,—75,—103·9, and their components along Ay are 70·7, 129·9,—60. The sums of these

two sets being respectively—108·2 and 140·6, we have $U \cos \phi = -108{\cdot}2$ and $U \sin \phi = 140{\cdot}6$.

therefore $$U^2 = (108{\cdot}2)^2 + (140{\cdot}6)^2$$

or $$U = 177{\cdot}4$$

therefore $$177{\cdot}4 \cos \phi = -108{\cdot}2, \text{ and } 177{\cdot}4 \sin \phi = 136{\cdot}7.$$

If we made use of the former of these equations only, we should obtain ϕ equal to 232° 25′, or 127° 35′, and the result would be ambiguous: in like manner if we determined ϕ from the second equation only, we should have ϕ equal to 52° 25′, or 127° 35′; but as we have both equations, we know that ϕ equals 127° 35′, and consequently the force U is completely determined as indicated by the dotted line AU.

35. **Conditions of equilibrium of any forces acting in one plane on a point.**—If the resultant of the forces is zero, they have no joint tendency to move the point, and consequently are in equilibrium. This obvious principle enables us to deduce the following constructions and equations, which serve to ascertain whether given forces will keep a point at rest.

Suppose that in the case represented in fig. 8, T is the force which will balance P, Q, R, S. It is plain that T must act on A along HA produced, and in magnitude must be proportional to HA; for then the resultant of the five forces will equal zero, since the broken line ABFGHA returns to the point A. This construction is plainly equivalent to the following: Let P, Q, R (fig. 10) be forces acting on the point O, as indicated, their magnitudes and directions being given. It is known that they are balanced by a fourth force, S, and it is required to determine the magnitude and direction of S. Take any point D, and draw any line parallel to and towards the same part as OP, draw AB parallel to and towards the same part as OQ, and take AB such that P : Q :: DA : AB. Through B draw BC parallel to and towards the same part as OR, taking BC such that Q : R :: AB : BC; join CD; through O draw OS parallel to and towards the same part as CD, then the required force S acts along OS, and is in magnitude proportional to CD.

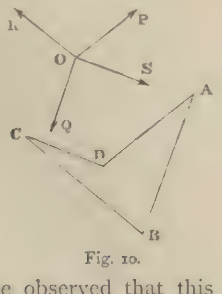


Fig. 10.

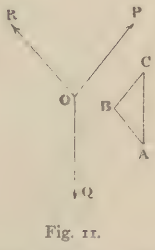


Fig. 11.

It is to be observed that this construction can be extended to any number of forces, and will apply to the case in which these directions are not in one plane, only in this case the broken line ABCD would not lie wholly in one plane. The above construction is frequently called the *Polygon of Forces.*

The case of three forces acting on a point is, of course, included in the above; but its importance is such that we may give a separate statement of it. Let P, Q, R (fig. 11) be three forces in equilibrium on the point O. From any point B draw BC parallel to and towards the same part OP, from C draw CA parallel to and towards the same part as OQ, and take CA such that P : Q :: BC : CA; then, on joining AB, the third force R must act along OR parallel to and towards the same part as AB, and must be proportional in magnitude to AB. This construction is frequently called the *Triangle of Forces.* It is evident that while the sides of the triangle are severally proportional to P, Q, R, the angles A, B, C are supplementary to QOR, ROP, POQ respectively, consequently every trigonometrical relation existing between the sides and angles of ABC will equally exist between the forces P, Q, R, and the supplements of the angles between their directions. Thus in the triangle ABC it is known that the sides are proportional to the sines of the opposite angles; now since the sines of the angles are equal to the sines of their supplements, we at once conclude that *when three forces are in equilibrium, each is proportional to the sine of the angle between the directions of the other two.*

We can easily obtain from the equations which determine the resultant of any number of forces (34), equations which express the conditions of equilibrium of any number of forces acting in one plane on a point: in fact, if U = o we must have X = o and Y = o; that is to say, the required conditions of equilibrium are these:—

$$o = P \cos \alpha + Q \cos \beta + R \cos \gamma + \ldots$$

and

$$o = P \sin \alpha + Q \sin \beta + R \sin \gamma + \ldots$$

The first of these equations shows that no part of the motion of the point can take place along Ax, the second that no part can take place along Ay. In other words, the point cannot move at all.

36. **Composition and resolution of parallel forces.**—The case of the equilibrium of three parallel forces is merely a particular case of the equilibrium of three forces acting on a point. In fact let P and Q be two forces whose directions pass through the points A and B, and intersect in O; let them be balanced by a third force R whose direction produced intersects the line AB in C. Now suppose the point O to move along AO, gradually receding from A, the magnitude and direction of R will continually change, and also the point C will continually change its position, but will always lie between A and B. In the limit P and Q become parallel forces, acting towards the same part balanced by a parallel force R acting towards the contrary part through a point X between A and B. The question is :—*First*, on this limiting case what is the value of R; *secondly*, what is the position of X. Now with regard to the first point it is plain, that if a triangle *a b c* were drawn as in art. 35, the angles *a* and *b* in the limit will vanish, and *c* will become 180°, consequently *a b* ultimately equals *a c* + *c b*

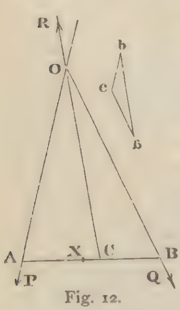


Fig. 12.

or

$$R = P + Q.$$

With regard to the second point it is plain that

$$OC \sin POR = OC \sin AOC = AC \sin CAO,$$

and $$OC \sin ROQ = OC \sin BOC = CB \sin CBO$$

therefore $$AC \sin CAO : CB \sin CBO :: \sin POR : \sin ROQ$$
$$:: Q : P \ (35)$$

Now in the limit when OA and OB become parallel, OAB and OBA become supplementary; that is, their sines become equal; also AC and CB become respectively AX and XB; consequently

$$AX : XB :: Q : P,$$

a proportion which determines the position of X. This theorem at once leads to the rules for the composition of any two parallel forces, viz.

I. When two parallel forces P and Q act towards the same part, at rigidly connected points A and B, their resultant is a parallel force acting towards the same part, equal to their sum, and its direction divides the line AB into two parts AC and CB inversely proportional to the forces P and Q.

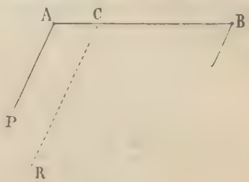


Fig. 13.

II. When two parallel forces P and Q act towards contrary parts, at rigidly connected points A and B of which P is the greater, their resultant is a parallel force acting towards the same part as P, equal to the excess of P over Q, and its direction divides BA produced in a point C such that CA and CB are inversely proportional to P and Q.

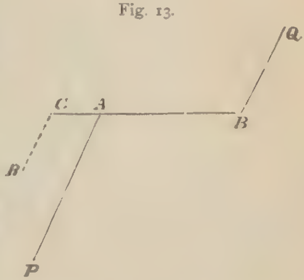


Fig. 14.

In each of the above cases if we were to apply R at the point C, in opposite direction to those shown in the figure, it would plainly (by the above theorem) balance P and Q, and therefore when it acts as shown in figs. 13 and 14 it is the resultant of P and Q in those cases respectively. It will of course follow that the force R acting at C can be resolved into P and Q acting at A and B respectively.

If the second of the above theorems be examined, it will be found that no force R exists equivalent to P and Q when those forces are equal. Two such forces constitute *a couple*, which may be defined to be two equal parallel forces acting towards contrary parts; they possess the remarkable property that they are incapable of being balanced by any single force whatsoever.

In the case of more than two parallel forces the resultant of any two can be found, then of that and a third, and so on to any number; it can be shown that however great the number of forces they will either be in equilibrium or reduce to a single resultant or to a couple.

37. **Centre of parallel forces.**—On referring to figs. 13 and 14, it will

be remarked that if we conceive the points A and B to be fixed in the directions AP and BQ of the forces P and Q, and if we suppose those directions to be turned round A and B, so as to continue parallel and to make any given angles with their original directions, then the direction of their resultant will continue to pass through C; that point is therefore called *the centre* of the parallel forces P and Q.

It appears from investigation, that whenever a system of parallel forces reduces to a single resultant, those forces will have a centre; that is to say, if we conceive each of the forces to act at a fixed point, there will be a point through which the direction of their resultant will pass when the directions of the forces are turned through any equal angles round their points of application in such a manner as to retain the parallelism of their directions.

The most familiar example of a centre of parallel forces is the case in which the forces are the weights of the parts of a body; in this case the forces all acting towards the same part will have a resultant, viz. their sum; and their centre is called the centre of gravity of the body.

38. **Moments of forces.**—Let P denote any force acting from B to P, take A any point, let fall AN a perpendicular from A on BP. The product of the number of units of force in P, and the number of units of length in AN is called the moment of P with respect to A. Since the force P can be represented by a straight line, the moment of P can be represented by an area. In fact if BC is the line representing P, the moment is properly represented by twice the area of the triangle ABC. The perpendicular AN is sometimes called the arm of the pressure. Now if a watch were placed with its face upward on the paper, the force P would cause the arm AN to turn round A in the *contrary* direction to the hands of the watch. Under these circumstances, it is usual to consider the moment of P with respect to the point A to be positive. If P acted from C to B, it would turn NA in the *same* direction as the hands of the watch, and now its moment is reckoned *negative*.

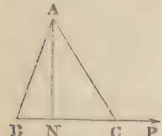


Fig. 15.

The following remarkable relation exists between any forces acting in one plane on a body and their resultant. Take the moments of the forces and of their resultant with respect to any one point in the plane. Then the moment of the resultant equals the sum of the moments of the several forces, regard being had to the *signs* of the moments.

If the point about which the moments are measured be taken in the direction of the resultant, its moment with respect to that point will be zero; and consequently the sum of the moments with respect to such point will be zero.

39. **Equality of Action and Reaction.**—We will proceed to exemplify some of the principles now laid down by investigating the conditions of equilibrium of bodies in a few simple cases; but before doing so we must notice a law which holds good whenever a mutual action is called into play between two bodies. *Reaction is always equal and contrary to action: that is to say, the mutual actions of two bodies on each other are*

always forces equal in amount and opposite in direction. This law is perfectly general, and is equally true when the bodies are in motion as well as when they are at rest. A very instructive example of this law has already been given (33), in which the action on the spring CD (fig. 6) is the weight W transmitted by the spring to C, and balanced by the reaction of the ground transmitted from B to D. Under these circumstances, the spring is said to be stretched by a force W. If the spring were removed, and the thread were continuous from A to B, it is clear that any part of it is stretched by two equal forces, viz. an action and reaction, each equal to W, and the thread is said to sustain a tension W. When a body is urged against a smooth surface, the mutual action can only take place along the common perpendicular at the point of contact. If, however, the bodies are rough, this restriction is partially removed, and now the mutual action can take place in any direction not making an angle greater than some determinate angle with the common perpendicular. This determinate angle has different values for different substances, and is sometimes called the *limiting angle of resistance*, sometimes the *angle of repose*.

40. **The Lever** is a name given to any bar straight or curved, AB, resting on a fixed point or edge c called the fulcrum. The forces acting on the lever are the *weight* or resistance Q, the *power* P, and the reaction of the fulcrum. Since these are in equilibrium, the resultant of P and Q must act through C, for otherwise they could not be balanced by the reaction. Draw cb at right angles to QB and ca to PA produced; then observing that $P \times ca$, and $Q \times cb$ are the moments of P and Q with respect to c, and that they have contrary signs, we have by (38),

$$P \times ca = Q \times cb;$$

an equation commonly expressed by the rule, that in the lever the power is to the weight in the inverse ratio of their *arms*.

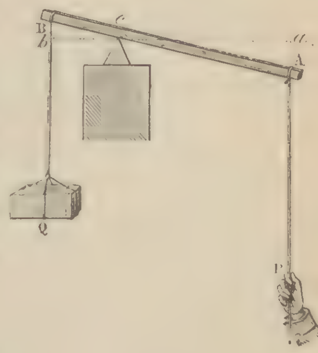


Fig. 16.

Levers are divided into three kinds, according to the position of the fulcrum with respect to the points of application of the power and the weight. In a *lever of the first kind* the fulcrum is between the power and resistance, as in fig. 16. In a *lever of the second kind* the resistance is between the power and the fulcrum, as in a wheelbarrow or a pair of nutcrackers; in a *lever of the third kind* the power is between the fulcrum and the resistance, as in a pair of tongs or the treadle of a lathe.

41. **The single pulley.**—In the case of the single fixed pulley, shown in fig. 17, it follows at once from (33) that when the forces P and Q are in equilibrium they will be equal, the axle of the pulley being supposed perfectly smooth and the thread perfectly flexible. The same conclusion

follows directly from the principle of moments; for the resultant of P and Q must pass through C, or otherwise they would cause the pulley to turn; now their moments are respectively P × CM and Q × CN, and since these have opposite signs we have (38)

$$P \times CM = Q \times CN.$$

But CM and CN being equal, this equation shows that P and Q are equal. In the case of the single moveable pulley, shown in fig. 18, we have one end of the rope fastened to a point A in a beam. The pulley is consequently supported by two forces, viz. P and the reaction of the fixed point which is equal to P; these two forces support Q and the weight of the pulley w. In the case represented in the figure the parts of the rope are parallel, consequently (36)

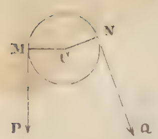


Fig. 17.

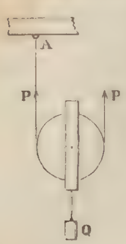


Fig. 18.

$$2P = Q + w.$$

When several pulleys are united into one machine, they constitute a *system* of pulleys; such are—the Block and Tackle, the Barton, White's Pulley, etc.

42. **The inclined plane.**—A very instructive and useful application of the resolution of forces is to be found in the case of a body supported on an inclined plane. Let AB (fig. 19) be the plane, AC its base, and BC its height; let a body M considered as a point, whose mass is M and weight Mg or Q, be supported on it by a force P acting along MB. The plane is supposed smooth, and therefore reacts on M with a force R at right angles to AB. Draw CD at right angles to AB, then the point M is held at rest by forces P, Q, R, whose directions are severally parallel to the sides of the triangle DBC which is similar to CBA. Hence

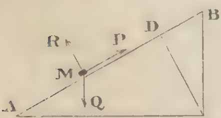


Fig. 19.

$$P : R : Q :: BD : DC : CB :: BC : CA : AB$$

or since $\quad BC = AB \sin A$ and $CA = AB \cos A$

we have $\quad P = Q \sin A$ and $R = Q \cos A$.

Or the same fact may be stated in this form;—When a mass M is placed on an inclined plane, its pressure on the plane is Mg cos A and its force down the plane is Mg sin A. In the above case these forces are balanced by P and R respectively.

Thus suppose BC and CA to be 9 ft. and 12 ft., respectively, then AB will equal 15 ft. Consequently, if the weight of Q is 360 lbs. it produces on the plane a perpendicular pressure of 288 lbs., and requires for its support a force of 216 lbs. acting up the plane.

43. **The wedge.**—This instrument is nothing but a moveable inclined plane. It is used in several forms, of which the annexed is, perhaps, the

best for showing the action of the forces called into play. AB is a fixed table. ACDE is a piece which is prevented from moving in a lateral direction by a fixed guide F. ABC is a wedge whose angle is such that one of its faces is in contact with a face of ACDE as shown in the figure. ABC being forced forward by P, overcomes the resistance Q acting on ACDE. The various forces called into play are represented in the diagram, namely, P, Q, the reaction of the table S, the mutual action between the pieces R, R_1 and the reaction T of the guide F. We will suppose the angles B, D, E, and EAB to be right angles, and that P and Q act at right angles to DE and BC respectively. Moreover, since the surfaces in contact are smooth, S acts in a direction at right angles to AB, R and R_1 to AC, and T to AE. Through C draw GG at right angles to AC; then the body ABC being kept in equilibrium by three forces, P, R, S, whose directions are respectively parallel to the sides of the triangle DGC, we have

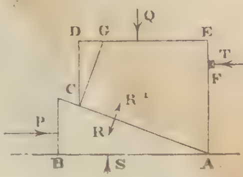


Fig. 20.

$$P : R :: DG : GC.$$

The body ACDE being kept in equilibrium by three forces, T, R_1, Q, whose directions are respectively parallel to the side of the triangle DGC, we have

$$R_1 : Q :: GC : CD.$$

Now R and R_1 are equal, being the mutual actions of the two bodies ABC, ACDE; therefore, compounding the ratios, we have

$$P : Q :: DG : DC$$

or, by similar triangles,

$$P : Q :: CB : BA$$

a proportion equivalent to the equation

$$P = Q \tan A.$$

44. **The screw.**—It will be remarked that when the wedge is used as in the last article, Q cannot be many times greater than P, and also that the space through which P can lift Q is limited. The screw is merely a modification of the wedge by which the limits of its application in both these respects are extended. To explain this it may be observed that if the thread of a screw were reduced to a line, it would become a curve called the *helix*, running in whorls round the cylinder; the distance between any two consecutive turns measured parallel to the axis of the cylinder being constant, and called the *pitch* of the screw. Now if ABC (fig. 20) were wrapped round a cylinder, whose dimensions were such that the base AB coincided with the circumference of the base of the cylinder, and the height BC with the pitch, the hypothenuse CA could be brought into coincidence with one whorl of the helix. Under these circumstances, the angle BAC (A) is called the *inclination of the thread*, and if r denote the radius of the base of the cylinder, h the pitch of the screw, we shall have, since AB tan A equals BC (fig. 20),

$$2\pi r \tan A = h.$$

Moreover, if ACDE were wrapped round the inside of a hollow cylinder or *nut* (fig. 21) of equal radius it would take the form of a helix, or companion screw cut on the inside of the nut; and if the screw were placed within the nut the two helices would be in exact contact. If now we suppose the power to act at the end of an arm, we shall have transformed the wedge of fig. 20 into a screw, one end of which works on a fixed table with a moveable nut. The annexed figure shows the arrangement, half the nut being removed in order to show how the thread of the screw works within the groove of the companion. When the arm is turned in the direction indicated by P the point B will pass to B′, but as the nut is kept by the guides G, H from turning with the screw, it must now occupy the point C of the companion, and consequently the nut must be lifted so that C comes to B′. If the nut were fixed the screw would be depressed by the same amount, when P acts as indicated.

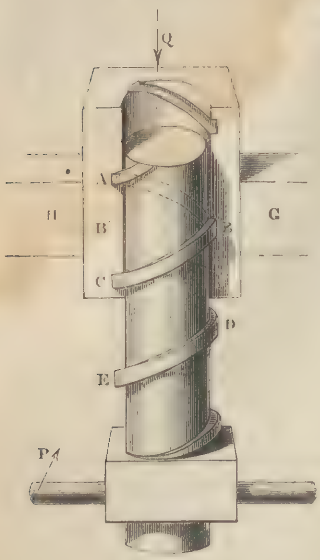


Fig. 21.

If the screw were turned by a force P′ acting tangentially to the base of the cylinder, it is plain that when all frictions are neglected the relation between P′ and Q must be the same as that between P and Q in the last article, that is,

$$P' = Q \tan A$$

or

$$2\pi r \, P' = Qh$$

but P acting perpendicularly at the end of an arm a will have (by equality of moments) the same tendency as P′ to turn the screw, provided

$$P'r = Pa$$

and therefore the relation between P and Q is given by the equation

$$2\pi a \, P = Qh$$

or the power has to the resistance the same ratio which the pitch of the screw has to the circumference of the circle described by the end of the arm; for example, if h equal 1 inch, and a equals 2 ft., a power of 100 lbs. would overcome a resistance not exceeding 15,000 lbs.

45. **Friction.**—To investigate the effect of the friction of the parts of machines on the relation connecting the power and resistance would take us far beyond our present limits, but the following points may be mentioned. If there were no friction there would generally be one ratio existing between the power and the resistance, that equilibrium may be

possible; thus in the single fixed pulley the ratio is one of equality, so that if P is not equal to Q (fig. 17) motion will ensue. If, however, the axle of the pulley is rough so as to turn with friction on its bearing, there will be two limiting ratios, such that if the ratio of P : Q have any intermediate value the machine will be at rest. Thus, suppose Q to be 20 lbs., the friction on the axle may be such that if P exceed 21 lbs., it will lift Q, and will allow Q to drop if it be less than 19 lbs. If P have any value intermediate to 19 and 21 it will balance Q. In the same manner on an inclined plane if the plane be smooth and if P act as supposed in (42) unless P were exactly equal to Q sin A, the body would move either up or down the plane. But if the plane be rough this is no longer true; there will in this case be two forces, namely, P' greater and P'' less than Q sin A, such that the former will just not draw the body up the plane, and the latter will just not allow the body to slide down the plane, and then any force P intermediate to P' and P'' will support Q. Moreover, if the body be left without support on the plane, it will slide down however small the inclination, if the plane be smooth, but if the plane be rough it will not slide down, though unsupported, unless the inclination exceed a certain angle, whose magnitude, though different for different substances, is virtually the same for the same substances, and is in fact the angle of repose mentioned in (39). This fact is of the utmost importance in the practical application of the wedge (54). For if the angle of inclination A of the wedge (fig. 20) be less than the angle of repose, Q will not force the wedge out, even when P ceases to act. Now in practice the wedge is commonly driven forward by a blow; but, as we shall see in sequel, a blow is a large force exerted for a short time, consequently a blow will cause a resistance Q, even when very great, to yield through a small space, thus each blow struck on the back of BC (fig. 20) will cause the wedge to advance a little, and, as Q cannot force it back, it will stay in the position to which it has been advanced, and consequently by a succession of such blows it can be caused to advance through any requisite space.

46. **Uniformly accelerated rectilinear motion.**—Let us suppose a body containing m units of mass to move from rest under the action of a force, containing F units, the body will move in the line of action of the force, and will acquire in each second an additional velocity f given by the equation

$$F = mf$$

consequently, if v is its velocity at the end of t seconds, we have

$$v = ft \qquad (1)$$

To determine the space it will describe in t seconds, we may reason as follows. The velocity at the time t being ft, that at a time $t+\tau$ will be $f(t+\tau)$. If the body moved uniformly during the time τ with the former velocity it would describe a space s equal to $ft\tau$, if with the latter velocity a space s_1 equal to $f(t+\tau)\tau$. Consequently,

$$s_1 : s :: t+\tau : t$$

therefore, when τ is indefinitely small, the limiting values of s and s_1 are equal. Now since the body's velocity is continually *increasing* during the time τ, the space actually described is greater than s and less than s_1. But since the limiting values of s and s_1 are equal, the limiting value of the space described is the same as that of s or s_1. In other words, if we suppose the whole time of the body's motion to be divided into any number of equal parts, if we determine the velocity of the body at the beginning of each of these parts, and if we ascertain the spaces described on the supposition that the body moves uniformly during each portion of time, the limiting value of the sum of these spaces will be the space actually described by the body.

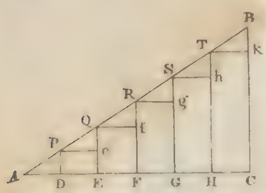


Fig. 22.

Draw a line AC, and at A construct an angle CAB, whose tangent equals f: divide AC into any number of equal parts in D, E, F,...and draw PD, QE, RF,...BC at right angles to AC, then since PD = AD × f, QE = AE × f, RF = AF × f, BC = AC × f, etc., PD will represent the velocity of the body at the end of the time represented by AD, and similarly QE, RF,... BC, will represent the velocity at the end of the times AE, AF,... AC. Complete the rectangles De, Ef, Fg... These rectangles represent the space described by the body on the above supposition during the second, third, fourth,... portions of the time. Consequently the space actually described during the time AC is the limit of the sum of the rectangles; the limit being continually approached as the number of parts into which AC is divided is continually increased. But this limit is the area of the triangle ABC; that is $\frac{1}{2}$AC × CB or $\frac{1}{2}$AC × AC × f. Therefore, if AC represents the time t during which the body describes a space s, we have

$$s = \tfrac{1}{2} ft^2 \tag{2}$$

Since this equation can be written

$$2fs = f^2t^2$$

we find, on comparing this with equation (1), that

$$v^2 = 2fs \tag{3}$$

To illustrate these equations let us suppose the accelerative effect of the force to be 6, that is to say, that in virtue of the action of the force, the body acquires in each successive second an additional velocity of 6 ft. per second, and let it be asked what, on the supposition of the body moving from rest, will be the velocity acquired and the space described at the end of 12 seconds; equations 1 and 2 enable us to answer that at that instant it will be moving at the rate of 72 ft. per second and will have described 432 ft.

The following important result follows from equation 2. At the *end* of the first, second, third, fourth, etc. second of the motion the body will have described $\frac{1}{2}f$, $\frac{1}{2}f \times 4$, $\frac{1}{2}f \times 9$, $\frac{1}{2}f \times 16$, etc. ft., and consequently *during* the first, second, third, fourth, etc. second of the motion will have

described $\frac{1}{2}f$, $\frac{1}{2}f \times 3$, $\frac{1}{2}f \times 5$, $\frac{1}{2}f \times 7$, etc. ft., namely, spaces in arithmetical progression.

The results of the above article can be stated in the form of laws which apply to the state of a body moving from a state of rest :—

I. *The velocities are proportional to the times during which the motion has lasted.*

II. *The spaces described are proportional to the squares of the times employed in their description.*

III. *The spaces described are proportional to the squares of the velocities acquired during their description.*

IV. *The spaces described in equal successive periods of time increase by a constant quantity.*

Instead of supposing the body to begin to move from a state of rest we may suppose it to have an initial velocity V, in the direction of the force. In this case equations 1, 2, and 3 can be easily shown to take the following forms respectively :

$$v = V + ft$$

$$s = Vt + \frac{1}{2}ft^2$$

$$v^2 = V^2 + 2fs$$

If the body move in a direction opposite to that of the force, f must be reckoned negative.

The laws stated in the present article apply directly to the case of a body falling freely in vacuo. In this case the force causing the acceleration is that of gravity, and it is usual to denote the acceleration produced, by the letter g; it has already been stated (27 and 29) that the numerical value of g, is 32·1912 at London, when the unit of time is a second and the unit of distance a foot.

47. **Motion on an inclined plane.**—Referring to (42), suppose the force P not to act; then the mass M is acted on by an unbalanced force Mg sin A, in the direction MA, consequently the accelerating force down the plane is g sin A, and the motion becomes a particular case of that discussed in the last article. If it begin to move from rest, it will at the end of t seconds acquire a velocity v given by the equation

$$v = gt \sin A$$

and will describe a length s (ft.) of the plane given by the equation

$$s = \tfrac{1}{2}gt^2 \sin A.$$

Also, if v is the velocity acquired while describing s feet of the plane

$$v^2 = 2gs \sin A.$$

Hence (fig. 19) if a body slides down the plane from B to A the velocity which it acquires at A equals $\sqrt{2g.\text{AB} \sin A}$ or $\sqrt{2g.\text{BC}}$. that is to say, the velocity which the body has at A does not depend on the angle A, but only on the perpendicular height BC. The same would be true if for BA we substituted any smooth curve, and hence we may state generally, that when a body moves along any smooth line under the action of gravity, the change of velocity it experiences in moving from

one point to another is that due to the *vertical* height of the former point above the latter.

48. **Composition of velocities.**—The rule for the composition of velocities is the same as that for the composition of forces; this follows evidently from the fact that forces are measured by the momentum they communicate, and are therefore to one another in the same ratio as the velocities they communicate to the *same* body. Thus (fig. 5, art. 33) if the point has at any instant a velocity AB, in the direction AP, and there is communicated to it a velocity AC in the direction AQ it will move in the direction AR with a velocity represented by AD. And conversely the velocity of a body represented by AD can be resolved into two component velocities AB and AC. This suggests the method of determining the motion of a body when acted on by a force in a direction transverse to the direction of its velocity; namely, suppose the time to be divided into a great number of intervals, and suppose the velocity actually communicated by the force to be communicated at once, then by the composition of velocities we can determine the motion during each interval, and therefore during the whole time; the actual motion is the limit to which the motion, thus determined, approaches when the number of intervals is increased.

49. **Motion in a circle.**—Let ABCD...be a regular polygon inscribed in a circle whose centre is O. Draw the diameter BOM. Produce AB to H, making BH equal to AB, join CH, this line is parallel to BO. Draw CK parallel to BH; and CL at right angles to BO. Join CM. Suppose a body whose mass is M to describe AB with a velocity V in a time t, suppose that at B there is suddenly communicated to it in the direction BO, a velocity ft which is the same velocity as a force Mf would communicate gradually in the same time t, it will move during the next short time t, with the velocity compounded of V and ft; now since BH equals Vt, if f is such that BK equals $ft \times t$, the body will describe BC, in the second interval. It will be observed that as BC and AB are equal and are described in equal times t, the velocity along BC is the same as along AB, that is, the effect of the composition is to change the direction, not the amount of the velocity. When the body is at the point C we may suppose a velocity ft to be communicated in the direction CO, and

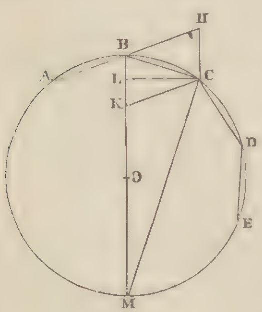


Fig. 23.

then at the end of the third interval the body will be at D. On this supposition therefore the body will describe the polygon ABCD... with a uniform velocity V. Now from similar triangles MCB, BCL we have

$$MB : BC :: BC : BL$$

or $$2r : Vt :: Vt : \tfrac{1}{2}(ft) \times t$$

where r denotes the radius of the circle;

therefore $$fr = V^2$$

This is true for all values of t, and therefore also when t is indefinitely small. Now by diminishing t we merely increase the number of sides of the polygon, therefore when t is indefinitely small, the motion takes place in the circle, and the force Mf acts continuously towards the centre.

This is a most important mechanical truth, it may therefore be well to illustrate as well as prove it. Suppose a mass containing 6 lbs. of matter to describe a circle whose radius is 5 ft. with an uniform velocity of 20 ft. per second. The force acting on it tending to the centre will contain $6 \times 20^2 \div 5$ or 480 units of force. In virtue of its inertia the body tends at each point to move along the tangent at that point, consequently a force must continually act on it *towards* the centre to deflect it from the tangent, and keep it moving in the circle; in the above case the force contains 480 units, which is nearly 15 lbs. of force.

50. **Motion in a vertical circle.**—Let ACDB be a circle whose plane is vertical and radius denoted by r. Suppose a point placed at A, and allowed to slide down the curve, what velocity will it have acquired on reaching any given point P? Draw the vertical diameter CD, join CA, CP, and draw the horizontal lines AMB and PNP′. Now assuming the curve to be smooth the velocity acquired in falling from A to P is that due to MN the vertical height of A above P (47); if, therefore, v denote the velocity of the point at P we shall have

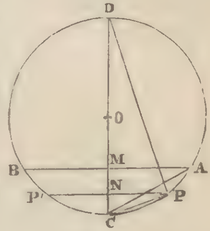


Fig. 24.

$$v^2 = 2g\,\text{MN}.$$

Now by similar triangles DCP, PCN we have

$$\text{DC} : \text{CP} :: \text{CP} : \text{CN}$$

consequently, if we denote by s the chord CP,

$$2r\,\text{NC} = s^2$$

in like manner if a denote the chord CA,

$$2r\,\text{MC} = a^2$$

therefore

$$2r\,\text{MN} = a^2 - s^2$$

and

$$v^2 = \frac{g}{r}(a^2 - s^2).$$

It will be remarked that v will have equal values when s has the same value whether positive or negative, and for any one value of s there are two equal values of v, one positive and one negative. That is to say, since CP′ is equal to CP, the body will have the same velocity at P′ that it has at P, and at any point the body will have the same velocity whether it is going up the curve or down the curve. Of course it is included in this statement, that if the body begins to move from A it will just ascend to a point B on the other side of C, such that A and B are in the same horizontal line. It will also be remarked that at C the value of s is zero;

consequently, if V is the velocity acquired by the body in falling from A to C we have

$$V = a\sqrt{\frac{g}{r}}$$

and, on the other hand, if the body begins to move from C with a velocity V it will reach a point A such that the chord AC or a is given by the same equation. In other words, the velocity at the lowest point is proportional to the chord of the arc described.

51. **Motion of a simple pendulum.**—By a simple pendulum is meant a heavy particle suspended by a fine thread from a fixed point, about which it oscillates without friction. So far as its changes of velocity are concerned they will be the same as those of the point in the previous article, for the tension of the thread acting at each position in a direction at right angles to that of the motion of the point, will no more affect its motion than the reaction of the smooth curve affects that of the point in the last article. The time of an oscillation, that is, the time in which the point moves from A to B, can be easily ascertained when the arc of vibration is small, that is, when the chord and the arc do not sensibly differ.

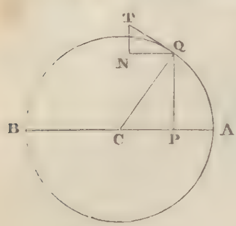


Fig. 25.

Thus, let AB (fig. 25) equal the arc or chord ACB (fig. 24), with centre C and radius AC or a describe a circle, and suppose a point to describe the circumference of that circle with a uniform velocity V or $a\sqrt{\frac{g}{r}}$. At any instant let the point be at Q, join CQ, draw the tangent QT, also draw QP at right angles and QN parallel to AB, then the angles NQT and CQP are equal. Now the velocity of Q resolved parallel to AB is V cos TQN or $a\sqrt{\frac{g}{r}}$ cos CQP, that is, if CP equals s, the velocity of Q parallel to AB is

$$\sqrt{\frac{g}{r}}\,\text{PQ} \text{ or } \sqrt{\frac{g}{r}(a^2-s^2)}.$$

But if we suppose a point to move along AB in such a manner that its velocity in each position is the same as that of the oscillating body, its velocity at P would also equal $\sqrt{\frac{g}{r}(a^2-s^2)}$; and, therefore, this point would describe AB in the same time that Q describes the semicircumference ACB. If then t be the required time of an oscillation we have

$$t = \pi a \div a\sqrt{\frac{g}{r}} = \pi\sqrt{\frac{r}{g}}.$$

This result is independent of the length of the arc of vibration, provided its *amplitude*, that is AB, be small. It is evident from the formula that the time of a vibration is directly proportional to the square root of the

length of the pendulum, and inversely proportional to the square root of the accelerating force of gravity.

As an example of the use of the formula we may take the following:—It has been found by careful experiment that 39·13983 inches is the length of a simple pendulum, whose time of oscillation at Greenwich is one second; the formula at once leads to an accurate determination of the accelerating force of gravity; for using feet and seconds as our units we have $t=1$, $r=3{\cdot}26165$, and π stands for the known number 3·14159, therefore the formula gives us

$$g=(3{\cdot}14159)^2\times 3{\cdot}26165=32{\cdot}1912.$$

This is the value employed in (29).

52. **Graphic representation of the changes of velocity of an oscillating body.**—The changes which the velocity of a vibrating body undergoes may be graphically represented as follows:—Draw a line of indefinite length and mark off AH to represent the time of one vibration, HH′ to represent the time of the second vibration, and so on. During the first vibration the velocity increases from zero to a maximum at the half

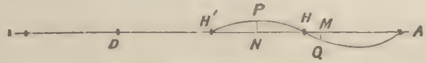


Fig. 26.

vibration, and then decreases during the second half vibration from the maximum to zero. Consequently, if a curved line or arc AQH is drawn, the ordinate QM at any point Q will represent the velocity of the body at the time represented by AM. If a similar curved line or arc HPH′ be drawn, the ordinate PN of any point P will represent the velocity at a time denoted by AN. But since the *direction* of the velocity in the second oscillation is contrary to that of the velocity in the first oscillation, the ordinate NP must be drawn in the contrary direction to that of MQ. If, then, the curve be continued by a succession of equal arcs alternately on opposite sides of AD, the variations of the velocity of the vibrating body will be completely represented by the varying magnitudes of the ordinates of successive points of the curve.

53. **Conical pendulum.**—When a point P is suspended from a point A as a simple pendulum, it can be caused to describe a horizontal circle with a uniform velocity V. A point moving in such a manner constitutes what is called a *conical pendulum*, and admits of many useful and interesting applications. We will, in this place, ascertain the relation which exists between the length r of the thread, AP, the angle of the cone PAN or θ, and the velocity V. Since the point P moves in a circle, whose radius is PN with a velocity V, a force R must act on it in the direction PN given by the equation (49)

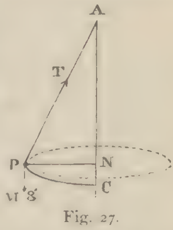


Fig. 27.

$$R=M\frac{V^2}{PN}$$

Now the only forces acting are the tension of the thread T along PA,

and the weight of the body Mg vertically, consequently their resultant must be a force R acting along PN. And therefore these forces will be parallel to the sides of the triangle ANP. So that (35)

$$R = Mg\frac{PN}{AN}$$

therefore

$$M\frac{V^2}{PN} = Mg\frac{PN}{AN}$$

or

$$V^2 = g\frac{PN^2}{AN}$$

Now

$$PN = r\sin\theta \text{ and } \frac{PN}{AN} = \tan\theta$$

therefore

$$V^2 = gr\sin\theta\tan\theta.$$

One conclusion from this may be noticed. With centre A and radius AP, describe the arc PC. Now when the angle PAC is small, the sine, PN, does not sensibly differ from the chord, nor the cosine, AN, from the radius, therefore in this case we have

$$V^2 = g\,.\,\frac{(\text{chd PC})^2}{\text{radius}} \text{ or } V = (\text{chd PC})\sqrt{\frac{g}{r}}$$

On comparing this result with (50) we see that when the angle PAN is small, the velocity of P moving in a conical pendulum is the same as P would have at the lowest point C if it oscillated as a simple pendulum; consequently, if we conceive the point P to be making small oscillations about the point A, and denote the velocity at the lowest point by V, and if when at the extreme point of the arc of vibration, there is communicated to it a velocity V in a direction at right angles to the plane of vibration, its motion will be changed into that of a conical pendulum.

54. **Impulsive forces.**—When a force acts on a body for an inappreciably short time, and yet sensibly changes its velocity, it is termed an *instantaneous* or *impulsive* force. Such a force is called into play when one body strikes against another. A force of this character is nothing but a finite though very large force, acting for a time so short that its duration is nearly, or quite, insensible. In fact, if M is the mass of the body, and the force contains Mf units, it will, in a time t, communicate a velocity ft; now, however small t may be, Mf and therefore f may be so large that ft may be of sensible or even considerable magnitude. Thus if M contain a pound of matter, and if the force contain ten thousand units, though t were so short as to be only the $\frac{1}{1000}$th of a second, the velocity communicated by the force would be one of 10 ft. per second. It is also to be remarked that the body will not sensibly move while this velocity is being communicated; thus, in the case supposed, the body would only move through $\frac{1}{2}ft^2$ or the $\frac{1}{200}$th of a foot while the force acts upon it.

When one body impinges on another it follows from the law of the equality of action and reaction (39) that whatever force the first body exerts upon the second, the second will exert an equal force upon the first in the opposite direction; now forces are proportional to the momenta generated in the same time; consequently, these forces generate, during the whole or any part of the time of impact, in the bodies respectively, equal momenta with contrary signs; and therefore the sum of the momenta of the two bodies will remain constant during and at the end of the impact. It is of course understood that if the two bodies move in contrary directions their momenta have opposite signs and the sum is an algebraical sum. In order to test the physical validity of this conclusion, Newton made a series of experiments which may be briefly described thus:—two balls A and B are hung from points C, D, in the same horizontal line by threads in such a manner that their centres A and B are in the same horizontal line. With centre C and radius CA describe a semicircle EAF, and with centre D and radius DB describe a semicircle GBH on the wall in front of which the balls hang. Let A be moved back to R, and be allowed to descend to A; it there impinges on B, both A and B will now move along the arcs AF and BH respectively, let A and B come to their highest points at r and k respectively. Now if V denote the velocity with which A reaches the lowest point, v and u the velocities with which A and B leave the lowest points after impact, and r the radius AC, it appears from (50) that

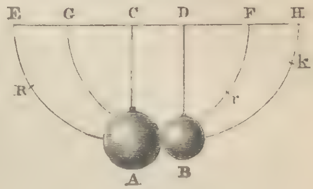


Fig. 28.

$$V = \text{chd AR}\sqrt{\frac{g}{r}},\quad v = \text{chd A}r\sqrt{\frac{g}{r}},\ \text{and}\ u = \text{chd B}k\sqrt{\frac{g}{r}}$$

therefore if A and B are the masses of the two balls, the momentum at the instant before impact was A × chd AR and the momentum after impact was $\text{A} \times \text{chd A}r + \text{B} \times \text{chd B}k$. Now when the positions of the points R, r, and k had been properly corrected for the resistance of the air, it was found that these two expressions were equal to within quantities so small that they could be properly referred to errors of observation. The experiment succeeded equally under every modification, whether A impinged on B at rest or in motion, and whatever the materials of A and B might be.

55. **Direct collision of two bodies.**—Let A and B be two bodies moving with velocities V and U respectively, along the same line, and let their mutual action take place in that line; if the one overtake the other what will be their respective velocities at the instant after impact? We will answer this question in two extreme cases.

i. Let us suppose the bodies to be *quite inelastic.* In this case, when A touches B, it will continue to press against B until their velocities are equalised, when the mutual action ceases. For whatever deformation the

bodies may have undergone, they have no tendency to recover their shapes. If, therefore, x is their common velocity after impact, we shall have $Ax + Bx$ their joint momentum at the end of impact, but their momentum before impact was $AV + BU$. Whence

$$(A + B)\,x = AV + BU$$

an equation which determines x.

ii. Let us suppose the bodies *perfectly elastic.* In this case they recover their shapes, with a force exactly equal to that with which they were compressed. Consequently the whole momentum lost by the one, and gained by the other, must be exactly double of that lost while compression took place, that is up to the instant at which their velocities were equalised. But these are respectively $AV - Ax$ and $Bx - BU$; therefore if v and u are the required final velocities

$$Av = AV - 2(AV - Ax) \text{ or } v = -V + 2x$$

$$Bu = BU + 2(Bx - BU) \text{ or } u = 2x - U$$

hence

$$(A + B)\,v = 2BU + (A - B)V$$

and

$$(A + B)\,u = 2AV - (A - B)U.$$

The following conclusion from these equations may be noticed: suppose a ball A, moving with a velocity V, to strike directly an equal ball B at rest. In this case $A = B$, and $U = 0$, consequently $v = 0$ and $u = V$, that is, the former ball A is brought to rest, and the latter B moves on with a velocity V. If now B strike on a third equal ball C at rest, B will in turn be brought to rest, and C will acquire the velocity V. And the same is true if there is a fourth, or fifth, or indeed any number of balls. This result may be shown with ivory balls, and if carefully performed is a very remarkable experiment.

56. **Work and energy.**—If the point of application of a force moves in a straight line, and if the part of the force resolved along this line acts in the direction of the motion, the product of that component and the length of the line is the work done by the force. If the component acts in the opposite direction to the motion, the component may be considered as a resistance and the product is work done against the resistance. Thus, in (42) if we suppose M to move up the plane from A to B, the work done by P is $P \times AB$; the work done against the resistance Q is $Q \sin A \times AB$. It will be observed that if the forces are in equilibrium during the motion, so that the velocity of M is uniform, P equals $Q \sin A$, and consequently the work done by the power equals that done against the resistance. Also since $AB \sin A$ equals BC the work done against the resistance equals $Q \times BC$. In other words, to raise Q from A to B requires the same amount of work as to raise it from C to B.

For strictly scientific purposes a unit of work is taken to be the work done by a unit of force when its point of application moves through one foot in the direction of its action. If, as is frequently done, a unit of work is defined to be a force of one pound exerted through one foot.

attention must be paid to the remark in (29) regarding the meaning of the term *pound* when considered as a unit of *force*. This unit may be conveniently distinguished as a 'foot-pound.' To raise a pound of matter through one foot requires more or less than a 'foot-pound' of work, according as the force of gravity on that pound of matter exceeds or falls short of 32·1912 units.

By the term *energy* or *vis viva* is meant a quantity proportional to the product of the mass of a body m and the square of its velocity v: it is most conveniently measured by $\frac{1}{2}mv^2$. If a force containing P units acts on a body whose mass is m, causing it to move from rest over h feet, the force will do Ph units of work, or if P equals mf it will do mfh units of work. Now if v is the velocity of the body at the end of the h feet, we know that v^2 equals $2fh$ (46). Therefore

$$\text{P}h \text{ or } mfh = \tfrac{1}{2}mv^2.$$

That is to say, *the work done by the force equals the energy of the body.* In the same manner, if the body have an initial velocity V, so that, when the force begins to act, it have already an energy $\frac{1}{2}m\text{V}^2$, the work done by the force will equal the change in the energy of the body or $\frac{1}{2}m(v^2-\text{V}^2)$.

It deserves particular notice that if the point of application of the force moves in a direction at right angles to that of the force, the force does no work, and therefore will not communicate energy to the body, nor cause its velocity to undergo change. A conspicuous example of this fact is furnished by the case of circular motion discussed in (49). Here the only force is $\text{MV}^2 \div r$, which acts on the body along the radius, and, therefore, at right angles to the direction of the motion at each instant; in consequence it does no work, and the velocity of the body is uniform.

57. **The conservation of energy.**—If we conceive a machine to move uniformly without friction it may be proved that the work done by the power exactly equals that done against the resistance. We have seen in (56) that this is the case with one simple machine—the inclined plane. It is obviously so too in the case of the screw; for, on examining (44) it is plain that if the arm makes one complete turn the resistance is raised through a height equal to the pitch of the screw. Now as P acts tangentially to the circle described by the end of the arm it does $2\pi a$ P units of work, and the work done against Q equals Qh, and these have been shown to be equal in the article (44) referred to. It can also be shown to be true in all other cases. This is the principle which is frequently stated thus:—that *what is gained in power is lost in velocity.* In fact, the whole efficacy and value of machines consist in this that, by diminishing the velocity of the point of application of the resistance, we may overcome the resistance, however large, by a given force.

If we suppose the machine to move subject to friction and with a variable velocity, the above principle undergoes the following extension. If the work done against the resistance, that done against the frictions of the parts of the machine, that which exists in the changed energy of the parts of the machine be added together, their sum will equal the work

done by the power. If we understand the term *machine* to mean any system of bodies moving, under the action of given forces, this principle is what has been generally called the conservation of *vis viva.*

This principle has of late undergone a remarkable extension, which may be explained as follows. Referring to (56) we have seen that to raise M from A to B requires $Mg \times BC$ units of work. Now if it fell from B to C it would acquire $Mg \times BC$ units of energy, consequently M placed at B may be held to contain $Mg \times BC$ units of *potential* energy more than when it is placed at C, or any other point in the horizontal line AC. Again, it has been ascertained that for every unit of work done against friction there is an exact equivalent of *heat*, and that amount of *heat* can be made to yield the same number of units of work. In like manner, when the form of a body is changed by the action of forces, either the work done against the internal forces will remain stored up as potential energy as in a compressed spring, or will have been replaced by the development of an equivalent of heat. Now this being premised we see that the energy communicated to any body, or system of bodies, is withdrawn from some fund of energy previously existing ; thus, the energy communicated to the piston of a steam engine is withdrawn from the *heat* of the steam : we also see that of the energy thus communicated none is destroyed, but is merely distributed, and exists either as potential energy, or as motion of the bodies acted on, or has been replaced by an equivalent of heat. This fact is called *the conservation of force*, or more properly the *conservation of energy.*

BOOK II.

GRAVITATION AND MOLECULAR ATTRACTION.

CHAPTER I.

GRAVITY, CENTRE OF GRAVITY, THE BALANCE.

58. **Universal attraction, its laws.**—*Universal attraction* is a force in virtue of which the material particles of all bodies tend incessantly to approach each other; it is a mutual action, however, which all bodies, at rest or in motion, exert upon one another, no matter how great or how small the space between them may be, or whether this space be occupied or unoccupied by other matter.

A vague hypothesis of the tendency of the matter of the earth and stars to a common centre was adopted even by Democritus and Epicurus. Kepler assumed the existence of a mutual attraction between the sun, the earth, and the other planets. Bacon, Galileo, and Hooke, also recognised the existence of universal attraction. But Newton was the first who established the law and the universality of gravitation.

Since Newton's time the attraction of matter by matter was experimentally established by Cavendish. This eminent English physicist succeeded by means of a delicate torsion balance (80) in rendering visible the attraction between a large leaden and a small copper ball.

The attraction between any two bodies is the resultant of the attractions of each molecule of the one upon every molecule of the other according to the law of Newton, which may be thus expressed: *the attraction between two material particles is directly proportional to the product of their masses, and inversely proportional to the square of their distances asunder.* To illustrate this, we may take the case of two spheres which, owing to their symmetry, attract each other just as if their masses were concentrated in their centres. If without other alteration the mass of one sphere were doubled, trebled, etc., the attraction between them would be doubled, trebled, etc. If, however, the mass of one sphere being doubled, that of the other were increased three times, the distance between their centres remaining the same, the attraction would be increased six times. Lastly, if, without altering their masses, the distance between their centres were *increased* from 1 to 2, 3, 4, ... units, the attraction would be *diminished* to the 4th, 9th, 16th, ... part of its former intensity. In short, if we define the unit of attraction as that which would exist between

two units of mass whose distance asunder was the unit of length, the attraction of two molecules, having the masses m and m', at the distance r, would be expressed by $\frac{m\,m'}{r^2}$.

59. **Terrestrial gravitation.**—The tendency of any body to fall towards the earth is due to the mutual attraction of that body and the earth ; or, to terrestrial gravitation, and is, in fact, merely a particular case of universal gravitation.

At any point of the earth's surface, the direction of gravity, that is the line which a falling body describes, is called the *vertical* line. The vertical lines drawn at different points of the earth's surface converge very nearly to the earth's centre. For points situated on the same meridian the angle contained between the vertical lines equals the difference between the latitudes of those points.

The directions of the earth's attraction upon neighbouring bodies, or upon different molecules of one and the same body, must, therefore, be considered as parallel, for the two vertical lines form the sides of a triangle whose vertex is near the earth's centre, about 4,000 miles distant, and whose base is the small distance between the molecules under consideration.

A plane or line is said to be *horizontal* when it is perpendicular to the vertical line.

The vertical line at any point of the globe is generally determined by the *plumb-line* (fig. 29), which consists of a weight attached to the end of a string. It is evident that the weight cannot be in equilibrium unless the direction of the earth's attraction upon it passes through the point of support, and therefore coincides with that of the string.

Fig. 29.

The horizontal plane is also determined with great ease, since it coincides, as will be afterwards shown, with the *level* surface of every liquid when in a state of equilibrium.

When the mean figure of the earth has been approximately determined, it becomes possible to compare the direction of the plumb-line at any place with that of the normal to the mean figure at that place. When any difference in these directions can be detected, it constitutes a *deviation* of the plumb-line, and is due to the attraction of some great mass of matter in the neighbourhood, such as a mountain. Thus in the case of the mountain of Schehallien, in Perthshire, it was found by Dr. Maskelyne that the angle between the directions of two plumb-lines, one at a station to the north, and the other to the south of the mountain, was greater by 11″ 6 than the angle between the normals of the mean surface of the earth at those points ; in other words, each plumb-line was deflected by about 6″ towards the mountain. By calculating the volume and mass of the mountain, it was inferred from this observation, that the mean density of the mountain was to that of the earth in the ratio of 5 : 9, and that the mean density of the earth is about five times that of water,—a result agreeing pretty

closely with that deduced from Cavendish's experiments referred to in the last article.

60. **Centre of gravity, its experimental determination.**—Into whatever position a body may be turned with respect to the earth, there is a certain point, invariably situated with respect to the body, through which the resultant of the attracting forces between the earth and its several molecules always passes. This point is called the *centre of gravity*; it may be within or without the body, according to the form of the latter: its existence, however, is easily established by the following considerations: Let m, m', m'', m'''. . . (fig. 30) be molecules of any body. The earth's attraction upon these molecules will constitute a system of parallel

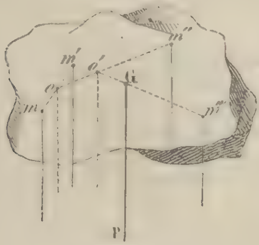


Fig. 30.

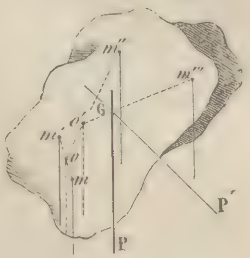


Fig. 31.

forces, having a common vertical direction, whose resultant, according to (36), will be found by seeking first the resultant of the forces which act on any two molecules, m, and m', then that of this resultant, and a third force acting on m'', and so on until we arrive at the final resultant, W, representing the weight of the body, and applied at a certain point G. If the body be now turned into the position shown in fig. 31, the molecules m, m', m''. . . . will continue to be acted on by the same forces as before, the resultant of the forces on m and m' will still pass through the same point o in the line mm', the following resultant will again pass through the same point o' in om'', and so on up to the final resultant P, which will still pass through the same point G, which is the *centre of gravity*.

To find the centre of gravity of a body is a purely geometrical problem; in many cases, however, it can be determined immediately. For instance, the centre of gravity of a right line of uniform density is the point which bisects its length; in the circle and sphere it coincides with the geometrical centre; in cylindrical bars it is the middle point of the axis. The centre of gravity of a plane triangle is in the line which joins any vertex with the middle of the opposite side, and at a distance from the vertex equal to two-thirds of this line; in a cone or pyramid it is in the line which joins the vertex with the centre of gravity of the base, and at a distance from the vertex equal to three-fourths of this line. These rules, it must be remembered, presuppose that the several bodies are of uniform density.

In order to determine experimentally the centre of gravity of a body, it is suspended by a string in two different positions as shown in figs. 32 and

33; the point where the directions AB and CD of the string in the two experiments intersect each other is the centre of gravity required. For the resultant of the earth's attraction being a vertical force applied at the

Fig. 32.

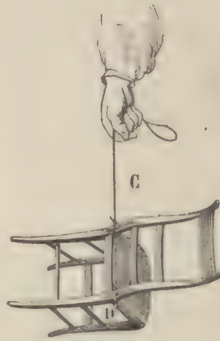


Fig. 33.

centre of gravity, the body can only be in equilibrium when this point lies vertically under the point of suspension, that is in the prolongation of the suspended string. But the centre of gravity being in AB as well as in CD must coincide with the point of intersection of these two lines.

61. **Equilibrium of heavy bodies.**—Since the action of gravity upon a body reduces itself to a single vertical force applied at the centre of gravity and directed towards the earth's centre, equilibrium will be established only when this resultant is balanced by the resultant of other forces and resistances acting on the body at the fixed point through which it passes.

When only one point of the body is fixed, it will be in equilibrium if the vertical line through its centre of gravity passes through the fixed point. If more than one point is supported, the body will be in equilibrium if a vertical line through the centre of gravity passes through a point within the polygon formed by joining the points of support.

The Leaning Tower of Pisa continues to stand because the vertical line drawn through its centre of gravity passes within its base.

It is easier to stand on our feet than on stilts, because in the latter case the smallest motion is sufficient to cause the vertical line through the centre of gravity of our bodies to pass outside the supporting base, which is here reduced to a mere line joining the feet of the stilts. Again, it is impossible to stand on one leg if we keep one side of the foot and head close to a vertical wall, because the latter prevents us from throwing the body's centre of gravity vertically above the supporting base.

62. **Different states of equilibrium.**—Although a body supported by a fixed point is in equilibrium whenever its centre of gravity is in the vertical line through that point, the fact that the centre of gravity tends

incessantly to occupy the lowest possible position leads us to distinguish between three states of equilibrium—*stable*, *unstable*, *neutral*.

A body is said to be in *stable equilibrium* if it tends to return to its first position after the equilibrium has been slightly disturbed. Every body is in this state when its position is such that the slightest alteration of the same elevates its centre of gravity; for the centre of gravity will descend again when permitted, and after a few oscillations the body will return to its original position.

The pendulum of a clock continually oscillates about its position of stable equilibrium, and an egg on a level table is in this state when its long axis is horizontal. We have another illustration in the toy represented in the adjoining fig. 34. A small figure cut in ivory is made to stand on one foot at the top of a pedestal by being loaded with two leaden balls, *a*, *b*, placed sufficiently low to throw the centre of gravity, *g*, of the whole compound body below the foot of the figure. After being disturbed the little figure oscillates like a pendulum, having its point of suspension at the toe, and its centre of gravity at a lower point, *g*.

Fig. 34.

A body is said to be in *unstable equilibrium*, when after the slightest disturbance it tends to depart still more from its original position. A body is in this state when its centre of gravity is vertically above the point of support, or higher than it would be in any adjacent position of the body. An egg standing on its end, or a stick balanced upright on the finger is in this state.

Lastly, if in any adjacent position a body stills remains in equilibrium, its state of equilibrium is said to be *neutral*. In this case an alteration in the position of the body neither raises nor lowers its centre of gravity. A perfect sphere resting on a horizontal plane is in this state.

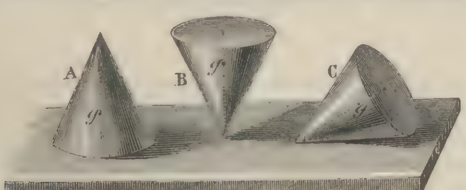


Fig. 35.

Fig. 35 represents three cones, A, B, C, placed respectively in stable, unstable, and neutral equilibrium upon a horizontal plane. The letter *g* in each shows the position of the centre of gravity.

63. **The balance.**—The balance is an instrument for determining the relative weights or masses of bodies. There are many varieties.

The ordinary balance (fig. 36) consists of a lever of the first kind, called

the *beam* AB, with its fulcrum in the middle ; at the extremities of the beam are suspended two scale pans, C and D, one intended to receive

Fig. 36

the object to be weighed, and the other the counterpoise. The fulcrum consists of a steel prism, *n*, commonly called a *knife edge*, which passes through the beam, and rests with its sharp edge, or *axis of suspension*, upon two supports ; these are formed of agate or polished steel, in order to diminish the friction. A needle or pointer is fixed to the beam, and oscillates with it in front of a graduated arc, *a* ; when the beam is perfectly horizontal the needle points to the zero of the graduated arc.

Since by (40) two equal forces in a lever of the first kind cannot be in equilibrium unless their leverages are equal, the length of the arms *n*A and *n*B ought to remain equal during the process of weighing. To secure this the scales are suspended from hooks, whose curved parts have sharp edges, and rest on similar edges at the ends of the beam. In this manner the scales are supported on mere points, which remain unmoved during

the oscillations of the beam. This mode of suspension is represented in fig. 36.

64. **Conditions to be satisfied by a balance.**—A good balance ought to satisfy the following conditions:

i. *The two arms of the beam ought to be precisely equal*, otherwise, according to the principle of the lever, unequal weights will be required to produce equilibrium. To test whether the arms of the beam are equal, weights are placed in the two scales until the beam becomes horizontal; the contents of the scales being then interchanged, the beam will remain horizontal if its arms are equal, but if not, it will descend on the side of the longer arm.

ii. *The balance ought to be in equilibrium when the scales are empty*, for otherwise unequal weights must be placed in the scales in order to produce equilibrium. It must be borne in mind, however, that the arms are not necessarily equal, even if the beam remains horizontal when the scales are empty; for this result might also be produced by giving to the longer arm the lighter scale.

iii. *The beam being horizontal, its centre of gravity ought to be in the same vertical line with the edge of the fulcrum, and a little below the latter*, for otherwise the beam would not be in stable equilibrium (62).

The effect of changing the position of the centre of gravity may be shown by means of a beam (fig. 37), whose fulcrum, being the nut of a screw, *a* can be raised or lowered by turning the screw-head, *b*.

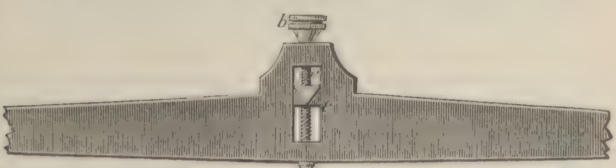


Fig. 37.

When the fulcrum is at the top of the groove *c*, in which it slides, the centre of gravity of the beam is below its edge, and the latter oscillates freely about a position of stable equilibrium. By gradually lowering the fulcrum its edge may be made to pass through the centre of gravity of the beam when the latter is in neutral equilibrium; that is to say, it no longer oscillates, but remains in equilibrium in all positions. When the fulcrum is lowered still more, the centre of gravity passes above its edge, the beam is in a state of unstable equilibrium, and is overturned by the least displacement.

65. **Delicacy of the balance.**—A balance is said to be *delicate* when a very small difference between the weights in the scales causes a perceptible deflection of the pointer.

Let A and B (figs. 38 and 39) be the points from which the scale pans are suspended, and C the axis of suspension of the beam. A, B, and C are supposed to be in the same straight line, according to the usual arrangement. Suppose weights P and Q to be in the pans suspended

from A and B respectively, and let G be the centre of gravity of the beam, then the beam will come to rest in the position shown in the figure where the line DCN is vertical, and ECG is the direction of the pointer.

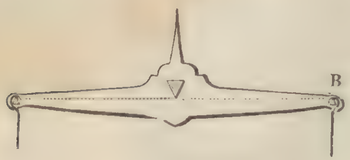


Fig. 38.

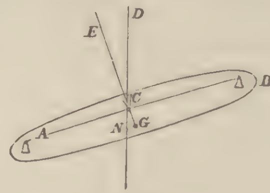


Fig. 39.

According to the above statement the greater the angle ECD for a given difference between P and Q the greater is the delicacy of the balance. Draw GN at right angles to CG.

Let W be the weight of the beam, then from the properties of the lever it follows that measuring moments with respect to C, the moment of P equals the sum of the moments of Q and W, a condition which at once leads to the relation

$$(P - Q)\ AC = W.\ GN$$

Now it is plain that for a given value of CG the angle GCN (that is ECD, which measures the delicacy) is greater as GN is greater: and from the formula it is plain that for a given value of P—Q we shall have GN greater as AC is greater, and as W is less. Again, for a given value of GN the angle GCN is greater as CG is less. Hence the means of rendering a balance delicate are :—

i. *To make the arms of the balance long.*

ii. *To make the weight of the beam as small as is consistent with its rigidity.*

iii. *To bring the centre of gravity of the beam a very little below the point of support.*

Moreover, since friction will always oppose the action of the force that tends to preponderate, the balance will be rendered more delicate by diminishing friction : to secure this advantage the edges from which the beam and scales are suspended are made as sharp as possible, and the supports on which they rest are very hard. And further, the pointer is made long, since its elongation renders a given deflection more perceptible by increasing the arc which its extremity describes.

66. **Physical and chemical balances.**—Fig. 40 represents one of the accurate balances ordinarily used for chemical analysis. Its sensitiveness is such that when charged with a kilogramme (1,000 grms.) in each scale, an excess of a milligramme ($\frac{1}{1000}$ of a grm.) in either scale produces a very perceptible deflection of the index.

In order to protect the balance from air-currents, dust, and moisture, it is always, even when weighing, surrounded by a glass case, whose front

slides up and down, to enable the operator to introduce the objects to be weighed.

In order to preserve the edge of the fulcrum as much as possible, the whole beam, BB, with its fulcrum K, can be raised from the support on

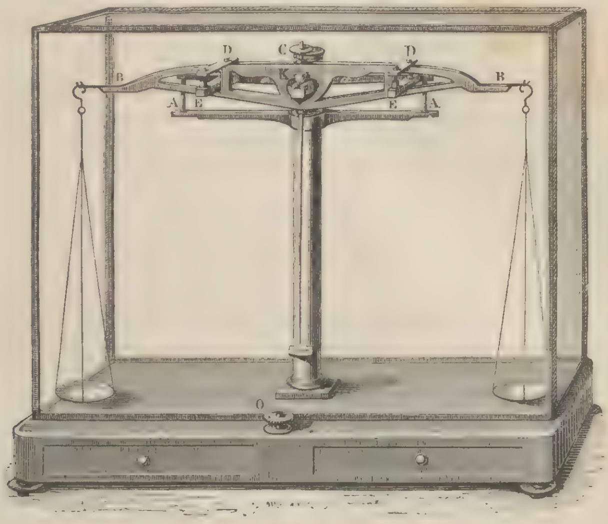


Fig. 40.

which the latter rests by simply turning the button O outside the case.

The horizontality of the beam is determined by means of a long index, which points downwards to a graduated arc near the foot of the supporting pillar.

Lastly, the button C serves to alter the sensitiveness of the balance; by turning it, the centre of gravity of the beam can be made to approach or recede from the fulcrum (64).

67. **Method of double weighing.**—Notwithstanding the inaccuracy of a balance, the true weight of a body may always be determined by its means. To do so, the body to be weighed is placed in one scale, and shot or sand poured into the other until equilibrium is produced; the body is then replaced by known weights until equilibrium is re-established. The sum of these weights will necessarily be equal to the weight of the body, for, acting under precisely the same circumstances, both have produced precisely the same effect.

CHAPTER II.

LAWS OF FALLING BODIES. INTENSITY OF TERRESTRIAL GRAVITY. THE PENDULUM.

68. **Laws of falling bodies.**—Since a body falls to the ground in consequence of the earth's attraction on *each* of its molecules, it follows that, everything else being the same, all bodies, great and small, light and heavy, ought to fall with equal rapidity, and a lump of sand without cohesion should, during its fall, retain its original form as perfectly as if it were compact stone. The fact that a stone falls more rapidly than a feather is due solely to the unequal resistances opposed by the air to the descent of these bodies; *in a vacuum all bodies fall with equal rapidity.* To demonstrate this by experiment a glass tube about two yards long (fig. 41) may be taken, having one of its extremities completely closed, and a brass cock fixed to the other. After having introduced bodies of different weights and densities (pieces of lead, paper, feather, etc.) into the tube, the air is withdrawn from it by an air pump, and the cock closed. If the tube be now suddenly reversed, all the bodies will fall equally quickly. On introducing a little air and again inverting the tube, the lighter bodies become slightly retarded, and this retardation increases with the quantity of air introduced.

The resistance opposed by the air to falling bodies is especially remarkable in the case of liquids. The Staubbach in Switzerland is a good illustration; an immense mass of water is seen falling over a high precipice, but before reaching the bottom it is shattered by the air into the finest mist. In a vacuum, however, liquids fall like solids without separation of their molecules. The *water hammer* illustrates this; the instrument consists of a thick glass tube about a foot long, half filled with water, the air having been expelled by ebullition previous to closing one extremity with the blow-pipe. When such a tube is suddenly inverted the water falls in one undivided mass against the other extremity of the tube, and produces a sharp dry sound, resembling that which accompanies the shock of two solid bodies.

From Newton's law (58) it follows, that when a body falls to the earth, the force of attraction which causes it to do so increases as the body approaches the earth. Unless the height from which the body falls, however, be very great, this increase will be altogether inappreciable, and the force in question may be considered as constant and continuous. If the resistance of the air were removed, therefore, the motion of all bodies falling to the earth would be uniformly accelerated, and would obey the laws already explained (46).

69. **Attwood's machine.**—Several instruments have been invented for illustrating and experimentally verifying the laws of falling bodies. Galileo, who discovered these laws in the early part of the seventeenth

century, illustrated them by means of bodies falling down inclined planes. The great object of all such instruments is to diminish the

Fig. 41.

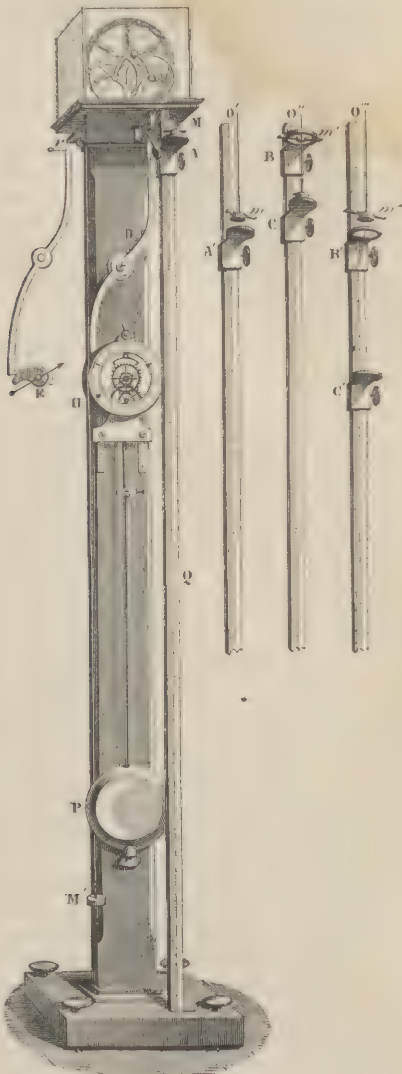


Fig. 42.

rapidity of the fall of bodies without altering the character of their motion,

for by this means their motion may not only be better observed, but it will be less modified by the resistance of the air.

The most convenient instrument of this kind is that invented by Attwood at the end of the last century, and represented in fig. 42. It consists of a stout pillar of wood about 2½ yards high, at the top of which is a brass pulley whose axle rests and turns upon four other wheels, called *friction wheels*, inasmuch as they serve to diminish friction. Two equal weights, M and M′, are attached to the extremities of a fine silk thread which passes round the pulley; a timepiece, H, fixed to the pillar, is regulated by a seconds pendulum, P, in the usual way—that is to say, the oscillations of the pendulum are communicated to a ratchet, whose two teeth, as seen in the figure, fit into those of the ratchet wheel. The axle of this wheel gives motion to the seconds hand of the dial, and also to an excentric behind the dial, as shown at E by a separate figure. This excentric plays against the extremity of a lever D, which it pushes until the latter no longer supports the small plate, *i*, and thus the weight M, which at first rested on this plate, is suddenly exposed to the free action of gravity. The excentric is so constructed that the little plate *i* falls precisely when the hand of the dial points to zero.

The weights M and M′ being equal hold each other in equilibrium; the weight M, however, is made to descend slowly by putting a small bar or overweight *m* upon it; and to measure the spaces which it describes, the rod or scale, Q, is divided into feet and inches, commencing from the plate *i*. To complete the instrument there are a number of plates, A, A′, C, C′, and a number of rings, B, B′, which may be fixed by screws at any part of the scale. The plates arrest the descending weight M, the rings only arrest the bar or overweight *m*, which was the cause of motion, so that after passing through them the weight M, in consequence of its inertia, will move on uniformly with the velocity it had acquired on reaching the ring. The several parts of the apparatus being described, a few words will suffice to explain the method of experimenting.

Let the hand of the dial be placed behind the zero point, the lever D adjusted to support the plate *i*, on which the weight M with its overweight *m* rests, and the pendulum put in motion. As soon as the hand of the dial points to zero the plate *i* will fall, the weights M and *m* will descend, and by a little attention and a few trials it will be easy to place a plate A so that M may reach it exactly as the dial indicates the expiration of one second. To make a second experiment, let the weights M and *m*, the plate *i*, and the lever D, be placed as at first; remove the plate A, and in its place put a ring, B, so as to arrest the overweight *m* just when the weight M would have reached A; on putting the pendulum in motion again it will be easy, after a few trials, to put a plate, C, so that the weight M may fall upon it precisely when the hand of the dial points to two seconds. Since the overweight *m* in this experiment was arrested by the ring B at the expiration of one second, the space BC was described by M in one second purely in virtue of its own inertia, and consequently, by (32) BC will indicate the velocity of the falling mass at the expiration of one second.

Proceeding in the same manner as before, let a third experiment be made in order to ascertain the point B′ at which the weight M and *m* arrive after the lapse of two seconds, and, putting a ring at B′, ascertain by a fourth experiment the point C′ at which M arrives alone, three seconds after the descent commenced; B′C′ will then express the velocity acquired after a descent of two seconds. In a similar manner, by a fifth and sixth experiment, we may determine the space OB″ described in three seconds, and the velocity B″C″ acquired during those three seconds, and so on; we shall find that B′C′ is twice, and B″C″ three times as great as BC—in other words, that the velocities BC, B′C′, B″C″, increase in the same proportion as the times (1, 2, 3, . . . seconds) employed in their acquirement. By the definition (46), therefore, the motion is uniformly accelerated. The same experiments will also serve to verify and illustrate the four laws of uniformly accelerated motion as enunciated in (46). For example, the spaces OB, OB′, OB″, ... described from a state of rest in 1, 2, 3, ... seconds, will be found to be proportional to the numbers 1, 4, 9, . . . that is to say, to the squares of those numbers of seconds, as stated in the third law.

Lastly, if the overweight *m* be changed, the acceleration or velocity BC acquired per second will also be changed, and we may easily verify the assertion in (29), that force is proportional to the product of the mass moved into the acceleration produced in a given time. For instance, assuming the pulley to be so light that its inertia can be neglected, if *m* weighed half an ounce, and M and M′ each $15\frac{3}{4}$ ounces, the acceleration BC would be found to be six inches; whilst if *m* weighed 1 ounce, and M and M′ each $63\frac{1}{2}$ ounces, the acceleration BC would be found to be three inches.

Now in these cases the forces producing motion, that is the overweights, are in the ratio of 1 : 2; while the products of the masses and the accelerations are in the ratio of $(\frac{1}{2} + 15\frac{3}{4} + 15\frac{3}{4}) \times 6$ to $(1 + 63\frac{1}{2} + 63\frac{1}{2}) \times 3$, that is, they are also in the ratio of 1 : 2. Now the same result is obtained in whatever way the magnitudes of *m*, M, and M′ are varied, and consequently in all cases the ratio of the forces producing motion equals the ratio of the momenta generated.

70. **Morin's apparatus.**—The principle of this apparatus, the original idea of which is due to General Poncelet, is to make the body in falling trace its own path. Figure 43 gives a view of the whole apparatus, and figure 44 gives the details. The apparatus consists of a wooden framework, about 7 feet high, which holds in a vertical position a very light wooden cylinder, M, which can turn freely about its axis. This cylinder is coated with paper divided into squares by equidistant horizontal and vertical lines. The latter measure the path traversed by the body falling along the cylinder, while the horizontal lines are intended to divide the duration of the fall into equal parts.

The falling body is a mass of iron, P, provided with a pencil which is pressed against the paper by a small spring. The iron is guided in its fall by two light iron wires which pass through guide-holes on the two sides. The top of this mass is provided with a tipper which catches

against the end of a bent lever, AC. This being pulled by the string K attached at A, the weight falls. If the cylinder M were fixed, the pencil would trace a straight line on it; but if the cylinder moves uniformly the pencil traces the line *mn*, which serves to deduce the law of the fall.

The cylinder is rotated by means of a weight, Q, suspended to a cord

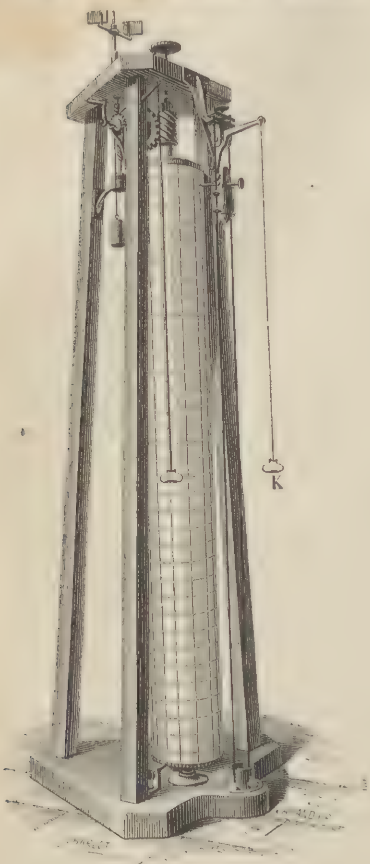


Fig. 43.

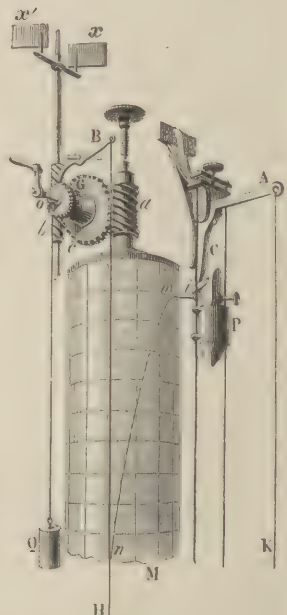


Fig. 44.

which passes round the axle G. At the end of this is a toothed wheel, *c*, which turns two endless screws, *a* and *b*, one of which turns the cylinder, and the other, two vanes, *x* and *x'*. At the other end is a ratchet wheel in which fits the end of a lever, B; by pulling at a cord fixed to the other end of B the wheel is liberated, the weight Q descends, and the whole system begins to turn. The motion is at first accelerated, but as the air

offers a resistance to the vanes, which increases as the rotation becomes more rapid, the resistance finally equals the acceleration which gravity tends to impart. From this time the motion becomes uniform. This is the case when the weight Q has traversed about three-quarters its course; at this moment the weight P is detached by pulling the cord K, and the pencil then traces the curve *mn*.

If, by means of this curve, we examine the double motion of the pencil on the small squares which divide the paper, we see that, for displacements of 1, 2, 3 . . . . in a horizontal direction, the displacements are 1, 4, 9 . . . . in a vertical direction. This shows that the paths traversed in the direction of the fall are directly as the squares of the lines in the direction of the rotation, which verifies the second law of falling bodies.

From the relation which exists between the two dimensions of the curve *mn*, it is concluded that this curve is a *parabola*.

71. **Length of the compound pendulum.**—The formula for the time of vibration of a simple pendulum, and the conclusions deduced from it (51) are also applicable to the compound pendulum, though in this case it will be necessary to define accurately what is meant by the *length* of such a pendulum. A compound pendulum being formed of a heavy rod terminated by a greater or less mass, it follows that the several material points of the whole system will strive to perform their oscillations in different times, their distances from the axis of suspension being different, and the more distant points requiring a longer time to complete an oscillation. From this, and from the fact that being points of the same body they must oscillate together, it follows that the motion of the points near the axis of suspension will be retarded, whilst that of the more distant points will be accelerated, and between the two extremities there will necessarily be a series of points whose motion will be neither accelerated nor retarded, but which will oscillate precisely as if they were perfectly free and unconnected with the other points of the system. These points, being equidistant from the axis of suspension, constitute a parallel axis known as the *axis of oscillation*; and it is to the distance between these two axes that the term *length of the compound pendulum* is applied : we may say, therefore, that *the length of a compound pendulum is that of the simple pendulum which would describe its oscillations in the same time.*

Huyghens, the celebrated Dutch physicist, discovered that the axes of suspension and oscillation are mutually convertible—that is to say, the time of oscillation will remain unaltered when the pendulum is suspended from its axis of oscillation. This remarkable fact enables us to determine experimentally the length of a compound pendulum. To do so the pendulum is inverted and suspended from a second and moveable axis, which, after some trials, is placed so that the inversion does not affect the number of oscillations made in a given time ; the length required is then the distance between the two axes, and on giving to l the value thus determined, the formula of (51) for the simple pendulum becomes appli-

cable to the compound pendulum, whose oscillations, *in vacuo*, obey the same laws.

The length of the *seconds* pendulum—that is to say, of the pendulum which makes one oscillation per second—varies, of course, with the intensity of gravity; at the level of the sea it is, according to Sabine,

39·02074 inches at the Equator (St. Thomas),
39·13983 „ at London, and
39·21469 „ at Spitzbergen.

According to the formula of (51), therefore, the accelerative effect of gravity at the above places is obtained by simply multiplying the above numbers reduced to feet by the square of 3·14159. Consequently $\frac{1}{2}g$ or the space described in the first second of its motion by a body falling *in vacuo* from a state of rest (46) is

16·0467 feet at the Equator,
16·0956 „ at London, and
16·1264 „ at Spitzbergen.

From observations of this kind, after applying the necessary corrections. and taking into account the effect of rotation (74), the form of the earth can be deduced.

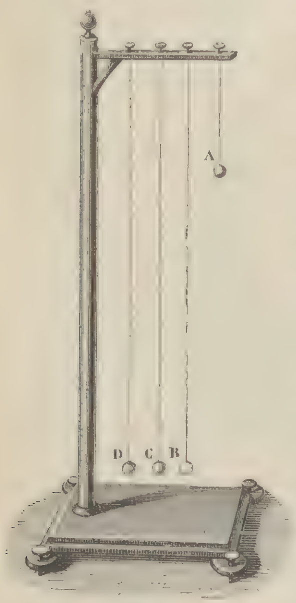


Fig. 45.

72. **Verification of the laws of the pendulum.**—In order to verify the laws of the simple pendulum (51) we are compelled to employ a compound one, whose construction differs as little as possible from that of the former. For this purpose a small sphere of a very dense substance, such as lead or platinum, is suspended from a fixed point by means of a very fine thread. A pendulum thus formed oscillates almost like a simple pendulum, whose length is equal to the distance of the centre of the sphere from the point of suspension.

In order to verify the isochronism of small oscillations, it is merely necessary to count the number of oscillations made in equal times, as the amplitudes of these oscillations diminish from 3 degrees to a fraction of a degree; this number is found to be constant.

That the time of vibration is proportional to the square root of the length is verified by causing pendulums, whose lengths are as the numbers 1, 4, 9, ... to oscillate simultaneously. The corresponding numbers of oscillations in a given time are then found to be

proportional to the fractions $1\ \frac{1}{2}$, $\frac{1}{3}$, etc. . . . . which shows that the times of oscillation increase as the numbers 1, 2, 3, ... etc.

By taking several pendulums of exactly equal length B, C, D (fig. 45), but with spheres of different substances, lead, copper, ivory, it is found that, neglecting the resistance of the air, these pendulums oscillate in equal times, thereby showing that the accelerative effect of gravity on all bodies is the same at the same place.

By means of an arrangement resembling the above, Newton verified the fact that the *masses* of bodies are determined by the balance; which, it will be remarked, lies at the foundation of the measure of force (29). For it will be seen on comparing (50) and (51) with (47) that the law of the time of a small oscillation is obtained on the supposition that the force of gravity on all bodies is represented by Mg, in which M is determined by the balance. In order to verify this, he had made two round equal wooden boxes; he filled one with wood, and as nearly as possible in the centre of oscillation of the other he placed an equal weight of gold. He then suspended the boxes by threads eleven feet long, so that they formed pendulums exactly equal so far as weight, figure, and resistance of the air were concerned. Their oscillations were performed in exactly the same time. The same results were obtained when other substances were used, such as silver, lead, glass, sand, salt, wood, water, corn. Now all these bodies had equal weights, and if the inference that therefore they had equal masses had been erroneous by so much as the one thousandth part of the whole, the experiment would have detected it.

73. **Application of the pendulum to clocks.**—The regulation of the motion of clocks is effected by means of pendulums, that of watches by balance-springs. Pendulums were first applied to this purpose by Huyghens in 1658, and in the same year Hooke applied a spiral spring to the balance of a watch. The manner of employing the pendulum is shown in fig. 46. The pendulum rod passing between the prongs of a fork *a* communicates its motion to a rod *b*, which oscillates on a horizontal axis *o*. To this axis is fixed a piece *mn* called an *escapement* or *crutch*, terminated by two projections or *pallets*, which work alternately with the teeth of the *escapement wheel* R. This wheel being acted on by the weight tends to move continuously, let us say, in the direction indicated by the arrow-head. Now if the pendulum is at rest, the wheel is held at rest by the pallet *m*, and with it the whole of the clockwork and the weight. If, however, the pendulum moves and takes the position shown by the dotted line, *m* is raised, the wheel *escapes* from the confinement in which it was held by the pallet, the weight descends, and causes the wheel to turn until its motion is arrested by the other pallet *n*; which in consequence of the motion of

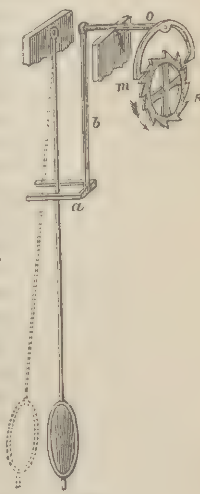


Fig. 46.

the pendulum will be brought into contact with another tooth of the escapement wheel. In this manner the descent of the weight is alternately permitted and arrested—or, in a word, regulated—by the pendulum. By means of a proper train of wheelwork the motion of the escapement is communicated to the hands of the clock; and consequently their motion, also, is regulated by the pendulum.

74. **Causes which modify the intensity of terrestrial gravitation.**—The intensity of the force of gravity at the earth's surface is modified by two causes, viz. by the form and by the rotation of the earth.

i. If the earth were a sphere of uniform density the resultant of the attractions which its parts exert on an external point would be the same as if the whole of its mass were collected at its centre, and therefore the attraction at all points of its surface would be the same. In consequence of the flattening of the earth at its poles, this is no longer exactly, but only very nearly true; and the attraction on an external point is only *nearly* inversely as the square of its distance from the earth's centre. As a further consequence of the flattening at the poles, the distance from the centre of a point on the surface decreases as we proceed from the equator to either pole; but as the distance decreases the attraction will increase, and consequently the force of gravity increases as the latitude increases, being least at the equator, and greatest at the poles. This is what would be true if, other things remaining the same, the earth were at rest.

ii. In consequence of the earth's rotation, the force of gravity undergoes a further modification. If we imagine a body relatively at rest on the equator, it really shares the earth's rotation, and describes, in the course of one day, a circle whose centre and radius are the centre and radius of the earth. Now since a body in motion tends by reason of its inertia to move in a straight line, it follows that to make it move in a circle, a force must be employed at each instant to deflect it from the tangent (49). Consequently a certain portion of the earth's attraction must be employed in keeping the above body on the surface of the earth, and only the remainder is sensible as *weight* or *accelerating force.* It appears from calculation that on the equator the $\frac{1}{289}$th part of the earth's attraction on any body is thus employed, so that the magnitude of g at the equator is less by the $\frac{1}{289}$th part of what it would be were the earth at rest. If the body, instead of being on the equator, is in any given latitude, it will describe in one day a circle coinciding with the *parallel of latitude* on which it is situated. Now when bodies describe in the same time circles of different radii, it can be deduced from (49) that the forces required to keep them in those circles are proportional to their radii. Hence the force required in the case of a body in any given latitude is less than that required if the body were on the equator, and less as the latitude is greater, consequently were gravity diminished by the whole amount of this force the diminution would be less the nearer the body is to either pole. But since the force is produced only by an indirect action of gravity, it appears that the diminution is thereby rendered still less as the latitude is greater. On the whole, therefore, the force of

gravity increases as we pass from the equator to either pole, in consequence of the rotation of the earth.

It will be observed that both causes, viz. the flattening of the earth at the poles, and its rotation, concur in producing an increase in the sensible force of gravity as the observer leaves the equator and approaches either pole.

CHAPTER III.

MOLECULAR FORCES.

75. **Nature of molecular forces.**—The various phenomena which bodies present show that their molecules are under the influence of two contrary forces, one of which tends to bring them together, and the other to separate them from each other. The first force, which is called *molecular attraction*, varies in one and the same body with the distance only. The second force, which is due to the action of heat, varies with the intensity of this agent, and with the distance. It is the mutual relation between these forces, the preponderance of the one or the other, which determines the molecular state of a body (4),—whether it be solid, liquid, or gaseous.

Molecular attraction is only exerted at infinitely small distances. Its effect is inappreciable when the distance between the molecules is appreciable. The laws which regulate this force are not known.

According to the manner in which it is regarded, molecular attraction is designated by the terms *cohesion*, *affinity*, or *adhesion*.

76. **Cohesion.**—*Cohesion* is the force which unites two molecules of the same nature; for example, two molecules of water, or two molecules of iron. Cohesion is strongly exerted in solids, less strongly in liquids, and scarcely at all in gases. Its intensity decreases as the temperature increases, because then the repulsive force due to heat increases. Hence it is that when solid bodies are heated they first liquefy, and are ultimately converted into the gaseous state, provided that heat produces in them no chemical change.

Cohesion varies not only with the nature of bodies, but also with the arrangement of their molecules; for example, the difference between tempered and untempered steel is due to a difference in the molecular arrangement produced by tempering. It is to the modifications which this force undergoes that many of the properties of bodies are due, such as tenacity, hardness, and ductility.

In large masses of liquids, the force of gravity overcomes that of cohesion. Hence liquids acted upon by the former force have no special shape; they take that of the vessel in which they are contained. But in smaller masses cohesion gets the upper hand, and liquids present then the spheroidal form. This is seen in the drops of dew on the leaves of plants; it is also seen when a liquid is placed on a solid which it does not moisten; as, for example, mercury upon wood. The experiment may

also be made with water, by sprinkling upon the surface of the wood some light powder, such as lycopodium or lampblack, and then dropping some water on it. The following pretty experiment is an illustration of the force of cohesion causing a liquid to assume the spheroidal form. A saturated solution of sulphate of zinc is placed in a narrow-necked bottle, and a few drops of bisulphide of carbon, coloured with iodine, made to float on the surface. If pure water be now carefully added, so as to rest on the surface of the sulphate of zinc solution, the bisulphide collects in the form of a flattened spheroid, which presents the appearance of blown coloured glass, and is larger than the neck of the bottle, provided a sufficient quantity has been taken.

77. **Affinity.**—*Chemical affinity* is the force which is exerted between molecules not of the same kind. Thus, in water, which is composed of oxygen and hydrogen, it is affinity which unites these elements, but it is cohesion which binds together two molecules of water. In compound bodies cohesion and affinity operate simultaneously, while in simple bodies cohesion has alone to be considered.

To affinity are due all the phenomena of combustion, and of chemical combination and decomposition.

The causes which tend to weaken cohesion are most favourable to affinity; for instance, the action of affinity between substances is facilitated by their division, and still more by reducing them to a liquid or gaseous state. It is most powerfully exerted by a body in its *nascent* state, that is, the state in which the body exists at the moment it is disengaged from a compound; the body is then free, and ready to obey the feeblest affinity. An increase of temperature modifies affinity differently under different circumstances. In some cases, by diminishing cohesion, and increasing the distance between the molecules, heat promotes combination. Sulphur and oxygen, which at the ordinary temperature are without action on each other, combine to form sulphurous acid when the temperature is raised: in other cases heat tends to decompose compounds by imparting to their elements an unequal expansibility. It is for this reason that many metallic oxides, as for example those of silver and mercury, are decomposed, by the action of heat, into gas and metal.

78. **Adhesion.**—The molecular attraction exerted between bodies in contact is called *adhesion.*

i. Adhesion takes place between solids. If two leaden bullets are cut with a penknife so as to form two equal and brightly polished surfaces, and the two faces are pressed and turned against each other until they are in the closest contact, they adhere so strongly as to require a force of more than 100 grammes to separate them. The same experiment may be made with two equal pieces of glass, which are polished and made perfectly plane. When they are pressed one against the other, the adhesion is so powerful that they cannot be separated without breaking. As the experiment succeeds in vacuo, it cannot be due to atmospheric pressure, but must be attributed to a reciprocal action between the two surfaces. The attraction also increases as the contact is prolonged, and is greater in proportion as the contact is closer.

ii. Adhesion also takes place between solids and liquids. If we dip a glass rod into water, on withdrawing it a drop will be found to collect at its lower extremity, and remain suspended there. As the weight of the drop tends to detach it, there must necessarily be some force superior to this weight which maintains it there: this force is the force of adhesion.

iii. The force of adhesion operates, lastly, between solids and gases. If a glass or metal plate be immersed in water, bubbles will be found to appear on the surface. As air cannot penetrate into the pores of the plate, the bubbles could not arise from the air which had been expelled. It is solely due to the layer of air which covered the plate, and *moistened* it like a liquid. In many cases when gases are separated in the nascent state on the surface of metals—as in electrolysis—the layer of gas which covers the plate has such a density that it is susceptible of very energetic chemical actions.

Under the heads *capillarity*, *endosmose*, *effusion*, *absorption*, and *imbibition*, we shall presently study a series of phenomena which are due to molecular attraction.

CHAPTER IV.

PROPERTIES PECULIAR TO SOLIDS.

79. **Various special properties.**—After having described the principal properties common to solids, liquids, and gases, we shall discuss the properties peculiar to solids. They are, *elasticity of traction*, *elasticity of torsion*, *elasticity of flexure*, *tenacity*, *ductility*, and *hardness*.

80. **Elasticity of traction.**—Elasticity, as a general property of matter, has been already mentioned (17), but simply in reference to the elasticity developed by pressure. In solids it may also be called into play by traction, by torsion, and by flexure.

In order to study the laws of the elasticity of traction, Savart used the apparatus represented in fig. 47. It consists of a wooden support from which are suspended the rods or wires taken for experiment. At the lower extremity there is a scale pan, and on the wire two points, A and B, are marked, the distance between which is measured by means of the *cathetometer*, before the weights are added.

The *cathetometer* consists of a strong brass support, K, divided into millimeters, and which can be adjusted in a vertical position by means of levelling screws and the plumb line. A small telescope, exactly at right angles to the scale, moves up and down, and is provided with a vernier which measures fiftieths of a millimeter. By fixing the telescope successively on the two points A and B, as represented in the figure, the distance between these points is obtained on the graduated scale. Placing then weights in the pan, and measuring again the distance A and B, the elongation is obtained.

When the limit of elasticity has not been exceeded, the traction of rods and wires is subject to the following laws :—

I. *Rods and wires possess perfect elasticity: that is, they assume their original length as soon as the traction ceases.*

II. *For the same substance and the same diameter, the elongation is proportional to the force of traction and to the length.*

III. *For rods or wires of the same length and substance, but of different magnitude, the elongation is in inverse ratio of the squares of the diameters.*

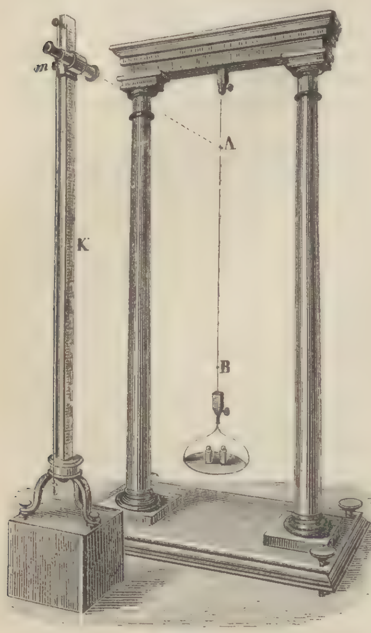


Fig. 47.

Fig. 48.

These laws can be expressed by the formula

$$e = \frac{Fl}{EA}$$

where e denotes the elongation, l the length, and A the area of the section of the rod, F the force tending to produce elongation, and E a constant depending on the material of the rod called the *modulus of elasticity*.

Both calculation and experiment show that when bodies are lengthened by traction their volume increases.

From numerous experiments on the elasticity of metals made by M. Wertheim it results that the modulus of elasticity changes as the tem-

perature varies. Between 15° and 200° he found the change to be generally one of decrease. Iron, and some specimens of steel, however, presented a conspicuous exception.

81. **Elasticity of torsion.**—The laws of the torsion of wires were determined by Coulomb, by means of an apparatus called the *torsion balance* (fig. 46). It consists of a metallic wire, clasped at its upper extremity in a support, A, and holding at the other extremity a metallic sphere, B, to which is affixed an index, C. Immediately below this there is a graduated circle, CD. If the needle is turned from its position of equilibrium through a certain angle which is the *angle of torsion*, the force necessary to produce this effect is called the *force of torsion.* When, after this deflection, the sphere is left to itself, the reaction of torsion produces its effect, the wire untwists itself, and the sphere rotates round its vertical axis with increasing rapidity until it reaches its position of equilibrium. It does not, however, rest there; in virtue of its inertia it passes this position, and the wire undergoes a torsion in the opposite direction. The equilibrium being again destroyed the wire again tends to untwist itself, the same alterations are again produced, and the needle does not rest at zero of the scale until after a certain number of oscillations about this point have been completed.

By means of this apparatus Coulomb found that when the amplitude of the oscillations is within certain limits, the oscillations are subject to the following laws:—

I. *The oscillations are very nearly isochronous.*

II. *For the same wire, the angle of torsion is proportional to the moment of the force of torsion.*

III. *With the same force of torsion, and with wires of the same diameter, the angles of torsion are proportional to the lengths of the wires.*

IV. *The same force of torsion being applied to wires of the same length, the angles of torsion are inversely proportional to the fourth powers of the diameters.*

Wertheim has examined the elasticity of torsion in the case of stout rods by means of a different apparatus, and finds that it is also subject to these laws. He has further found that, all dimensions being the same, different substances undergo different degrees of torsion, and each substance has its own coefficient of torsion, which is denoted by $\frac{1}{T}$.

The laws of torsion may be enunciated in the formula $w = \frac{1}{T}\frac{Fl}{r^4}$; in which w is the angle of torsion, F the moment of the force of torsion, l the length of the wire, r its diameter, and $\frac{1}{T}$ the specific torsion-coefficient.

82. **Elasticity of flexure.**—A solid, when cut into a thin plate, and fixed at one of its extremities, after having been more or less bent, strives to return to its original position when left to itself. This property is very distinct in steel, caoutchouc, wood, and paper.

The elasticity of flexure is applied in a vast variety of instances, for

example in bows, watch springs, carriage springs ; in spring balances it is used to determine weights, in dynamometers to determine the force of agents on prime movers ; and, as existing in wool, hair, and feathers, it is applied to domestic uses in cushions and mattresses.

Whatever be the kind of elasticity, there is, as has been already said, a limit to it—that is, there is a molecular displacement, beyond which bodies are broken, or at any rate do not regain their primitive form. This limit is affected by various causes. The elasticity of many metals is increased by *hardening*, whether by cold, by means of the draw-plate, by rolling, or by hammering. Some substances, such as steel, cast iron, and glass, become both harder and more elastic by tempering (86).

Elasticity, on the other hand, is diminished by *annealing*, which consists in raising the body to a temperature lower than that necessary for tempering, and allowing it to cool slowly. It is by this means that the elasticity of springs may be regulated at pleasure. Glass, when it is heated, undergoes a true tempering in being rapidly cooled, and hence, in order to prevent too great a fragility of glass objects, they are reheated in a furnace, and are carefully allowed to cool slowly, so that the particles have time to assume their most stable position.

83. **Tenacity.**—*Tenacity* is the resistance which bodies oppose to traction. It is determined in different bodies by forming them into cylindrical or prismatic wires, and ascertaining the weight necessary to break them.

Tenacity is directly proportional to the breaking weight, and inversely proportional to the area of a transverse section of the wire.

Tenacity diminishes with the duration of the traction. A small force continuously applied for a long time will often break a wire, which would not at once be broken by a larger weight.

Not only does tenacity vary with different substances, but it also varies with the form of the body. Thus, with the same sectional area, a cylinder has greater tenacity than a prism. The quantity of matter being the same, a hollow cylinder has greater tenacity than a solid one ; and the tenacity of this hollow cylinder is greatest when the external radius is to the internal one in the ratio of 11 to 5.

The shape has also the same influence on the resistance to crushing, as it has on the resistance to traction. A hollow cylinder with the same mass, and the same weight, offers a greater resistance than a solid cylinder. It is for this reason that the bones of animals, the feathers of birds, the stems of corn and other plants, offer greater resistance than if they were solid, the mass remaining the same.

Tenacity, like elasticity, is different in different directions in bodies. In wood, for example, both the tenacity and the elasticity are greater in the direction of the fibres than in a transverse direction. And this difference obtains in general in all bodies, the texture of which is not the same in all directions.

The following table gives the breaking weight in pounds for wires having a sectional area of a square millimeter :

Antimony, cast	1·47	Copper, annealed	69·52
Bismuth, „	2·13	„ drawn	90·20
Lead, „	4·86	Iron, annealed	110·55
„ drawn	5·19	„ drawn	140·71
Tin „	6·60	Cast steel, drawn	184·36
„ cast	9·15		
Zinc, annealed	31·68	*Wood in the direction of the fibres.*	
„ drawn	34·58		
Gold, annealed	24·20	Mahogany	11·0
„ drawn	61·60	Oak	15·4
Silver, annealed	36·08	Beech	17·6
„ drawn	63·80	Fir	19·8
Platinum, annealed	58·85	Ash	26·4
„ drawn	77.00	Box	30·8

In this table the bodies are supposed to be at the ordinary temperature. At a higher temperature the tenacity rapidly decreases. M. Seguin, sen., who has recently made some experiments on this point with iron and copper, has obtained the following values for the tenacity, in pounds, of millimeter wire at different temperatures :

Iron	at 10°, 132·0;	at 370°, 118·8 ;	at 500°, 77·0;
Copper	„ 46·2 ;	„ 16·9 ;	„ 0.

84. **Ductility.**—*Ductility* is the property in virtue of which a great number of bodies change their forms by the action of traction or pressure.

With certain bodies, such as clay, wax, etc., the application of a very little force is sufficient to produce a change; with others, such as the resins and glass, the aid of heat is needed, while with the metals, more powerful agents must be used, such as percussion, the draw-plate, or the rolling-mill.

Malleability is that modification of ductility which is exhibited by hammering. The most malleable metal is gold, which has been beaten into leaves about the $\frac{1}{300000}$ of an inch thick.

The most ductile metal is platinum. Wollaston obtained a wire of it 0·00003 of an inch in diameter. This he effected by covering with silver a platinum wire 0·01 of an inch in diameter, so as to obtain a cylinder 0·2 inch in diameter only, the axis of which was of platinum. This was then drawn out in the form of wire as fine as possible ; the two metals were equally extended. When this wire was afterwards treated with dilute nitric acid the silver was dissolved, and the platinum wire left intact. The wire was so fine that 1,060 yards only weighed 0·75 of a grain.

85. **Hardness.**—*Hardness* is the resistance which bodies offer to being scratched or worn by others. It is only a relative property, for a body which is hard in reference to one body may be soft in reference to others. The relative hardness of two bodies is ascertained by trying which of them will scratch the other. Diamond is the hardest of all bodies, for it scratches all, and is not scratched by any. The hardness of a body is expressed by referring it to a *scale of hardness* : that usually adopted is—

1. Talc	5. Apatite	8. Topaz
2. Rock salt	6. Felspar	9. Corundum
3. Calcspar	7. Quartz	10. Diamond
4. Fluorspar		

Thus the hardness of a body which would scratch felspar, but would be scratched by quartz, would be expressed by the number 6·5.

The pure metals are softer than their alloys. Hence it is that for jewellery and coinage gold and silver are alloyed with copper to increase their hardness.

The hardness of a body has no relation to its resistance to compression. Glass and diamond are much harder than wood, but the latter offers far greater resistance to the blow of a hammer. Hard bodies are often used for polishing powders; for example, emery, pumice, and tripoli. Diamond, being the hardest of all bodies, can only be ground by means of its own powder.

86. **Temper.**—By sudden cooling after they have been raised to a high temperature, many bodies acquire great hardness. This operation is called *tempering.* All cutting instruments are made of tempered steel. There are, however, some few bodies upon which tempering produces quite a contrary effect. An alloy of one part of tin and four parts of copper, called *tamtam metal*, is ductile and malleable when rapidly cooled, but hard and brittle as glass when cooled slowly.

BOOK III.

ON LIQUIDS.

CHAPTER I.

HYDROSTATICS.

87. **Object of Hydrostatics.**—The science of *hydrostatics* treats of the conditions of the equilibrium of liquids, and of the pressures they exert, whether within their own mass or on the sides of the vessels in which they are contained.

The science which treats of the motion of liquids is *hydrodynamics* and the application of the principles of this science to conducting and raising water in pipes is known by the name of *hydraulics*.

88. **General characters of liquids.**—It has been already seen (4) that liquids are bodies whose molecules are displaced by the slightest force. Their fluidity, however, is not perfect, there is always a sufficient adherence between their molecules to produce a greater or less viscosity.

Gases also possess fluidity, but in a higher degree than liquids. The distinction between the two forms of matter is that liquids are almost incompressible and are comparatively inexpansible, while gases are eminently compressible, and expand spontaneously.

The fluidity of liquids is seen in the readiness with which they take all sorts of shapes. Their compressibility is established by the following experiment.

89. **Compressibility of liquids.**—From the experiment of the Florentine Academicians (13), liquids were for a long time regarded as being completely incompressible. Since then, researches have been made on this subject by various physicists, which have shown that liquids are really compressible.

The apparatus used for measuring the compressibility of liquids has been named the *piezometer* (πιέζω, I compress, μέτρον, measure.) That shown in fig. 49 is the form invented by Oersted as improved by MM. Despretz and Saigey ; it consists of a strong glass cylinder with very thick sides and an internal diameter of about $3\frac{1}{4}$ inches. The base of the cylinder is firmly cemented into a wooden foot, and on its upper part is fitted a metallic cylinder closed by a cap which can be unscrewed. In this cap there is a funnel, R, for introducing water into the cylinder, and a small barrel hermetically closed by a piston, which is moved by a screw, P.

In the inside of the apparatus there is a glass vessel, A, containing the liquid to be compressed. The upper part of this vessel terminates in a capillary tube, which dips under mercury, O. This tube has been previously divided into parts of equal capacity, and it has been determined how many of these parts the vessel A contains. The latter is ascertained by finding the weight, P, of the mercury which the reservoir, A, contains, and the weight, p, of the mercury contained in a certain number of divisions, n, of the capillary tube. If N be the number of divisions of the small tube contained in the whole reservoir, we have $\frac{N}{n} = \frac{P}{p}$, from which the value of N is obtained. There is further a *manometer*. This is a glass tube, B, containing air, closed at one end, and the lower extremity of which dips under mercury. When there is no pressure on the water in the cylinder, the tube B is completely full of air; but when the water within the cylinder is compressed by means of the screw P, the pressure is transmitted to the mercury, which rises in the tube, compressing the air which it contains. A graduated scale fixed on the side of the tube shows the reduction of volume, and this reduction of volume indicates the pressure exerted on the liquid in the cylinder, as will be seen in speaking of the manometer.

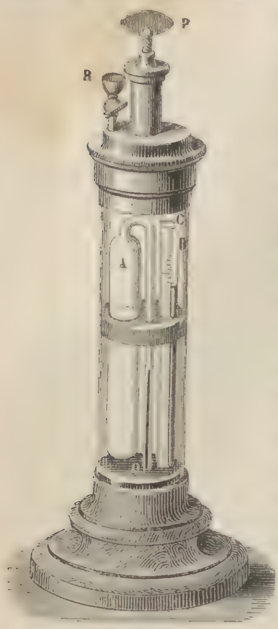


Fig. 49.

In making the experiment, the vessel A is filled with the liquid to be compressed, and the end dipped under the mercury. By means of the funnel R the cylinder is entirely filled with water. The screw P being then turned the piston moves downwards, and the pressure exerted upon the water is transmitted to the mercury and the air; in consequence of which the mercury rises in the tube, B, and also in the capillary tube. The ascent of mercury in the capillary tube shows that the liquid in the vessel A has diminished in volume, and gives the amount of its compression, for the capacity of the whole vessel A in terms of the graduated divisions on the capillary tube has been previously determined.

In his first experiments, Oersted assumed that the capacity of the vessel A remained the same, its sides being compressed both internally and externally by the liquid. But mathematical analysis proves that this capacity diminishes in consequence of the external and internal pressures. Colladon and Sturm have made some experiments allowing for this change of capacity, and have found that for a pressure equal to that of the atmosphere, mercury experiences a compression of 0·000005 parts of its original

volume; water a compression of 0·00005, and ether a compression of 0·000133 parts of its original bulk.

For water and mercury it was also found that within certain limits the decrease of volume is proportional to the pressure.

Whatever be the pressure to which a liquid has been subjected, experiment shows that as soon as the pressure is removed the liquid regains its original volume, from which it is concluded that *liquids are perfectly elastic.*

90. **Equality of pressures, Pascal's law.**—By considering liquids as perfectly fluid, and assuming them to be uninfluenced by the action of gravity, the following law has been established. It is often called Pascal's law, for it was first enunciated by that distinguished geometrician.

Pressure exerted anywhere upon a mass of liquid is transmitted undiminished in all directions, and acts with the same force on all equal surfaces, and in a direction at right angles to those surfaces.

To get a clearer idea of the truth of this principle, let us conceive a vessel of any given form in the sides of which are placed various cylindrical apertures, all of the same size, and closed by moveable pistons. Let us, further, imagine this vessel to be filled with liquid and withdrawn from the action of gravity; the pistons will, obviously, have no tendency to move. If now upon the piston A (fig. 50), which has a surface a, a weight of P pounds be placed, it will be pressed inwards, and the pressure will be transmitted to the internal faces of each of the pistons, B, C, D, and E, which will each be forced outwards by a pressure P, their surfaces being equal to that of the first piston. Since each of the pistons undergoes a pressure P, equal to that on A, let us suppose two of the pistons united so as to constitute a surface $2a$, it will have to support a pressure 2P. Similarly, if the piston were equal to $3a$, it would experience a pressure of 3P; and if its area were 100 or 1,000 times that of a, it would sustain a pressure of 100 or 1,000 times P. In other words, the pressure on any part of the internal walls of the vessel would be proportional to the surface.

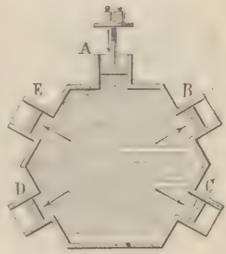


Fig. 50.

The principle of the equality of pressure is assumed as a consequence of the constitution of fluids. By the following experiment it can be shown that pressure is transmitted in all directions, although it cannot be shown that it is equally transmitted. A cylinder provided with a piston is fitted into a hollow sphere (fig. 51), in which small cylindrical jets are placed perpendicular to the sides. The sphere and the cylinder being both filled with water, when the piston is moved the liquid spouts forth from all the orifices, and not merely from that which is opposite to the piston.

The reason why a satisfactory quantitative experimental demonstration of the principle of the equality of pressure cannot be given is, that the influence of the weight of the liquid and of the friction of the pistons cannot be eliminated.

Yet an approximate verification may be effected by the experiment represented in fig. 52. Two cylinders of different diameters are joined

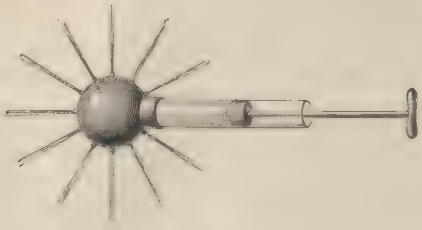


Fig. 51.

by a tube and filled with water. On the surface of the liquid are two pistons P and p, which hermetically close the cylinders, but move with friction. Let the area of the large piston be, for instance, thirty times that of the smaller one. That being assumed, let a weight, say of two pounds, be placed upon the small piston, this pressure will be transmitted to the water and to the large piston, and as this pressure amounts to two pounds *on each portion of its surface equal to that of the small piston*, the large piston must support an upward pressure thirty times as much, or of sixty pounds. If now this weight be placed upon the large piston, both will remain in equilibrium; but if the weight is greater or less, this is no longer the case. If S and s are the areas of the large and small piston respectively, then, $\frac{P}{p} = \frac{S}{s}$; whence $P = \frac{pS}{s}$.

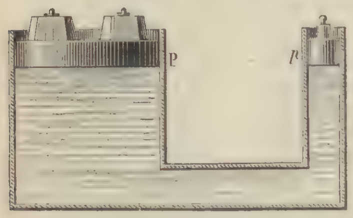


Fig. 52.

It is important to observe that in speaking of the transmission of pressures to the sides of the containing vessel, these pressures must always be supposed to be perpendicular to the sides; for any oblique pressure may be decomposed into two others, one at right angles to the side, and the other acting parallel with the side; but as the latter has no action on the side, the perpendicular one is the only one to be considered.

PRESSURE PRODUCED IN LIQUIDS BY GRAVITY.

91. **Vertical downward pressure, its laws.**—Any given liquid being in a state of rest in a vessel, if we suppose it to be divided into horizontal layers of the same density, it is evident that each layer supports the weight of those above it. Gravity, therefore, produces internal pressures

in the mass of a liquid which vary at different points. These pressures are submitted to the following general laws :—

I. *The pressure in each layer is proportional to the depth.*

II. *With different liquids and the same depth, the pressure is proportional to the density of the liquid.*

III. *The pressure is the same at all points of the same horizontal layer.*

The first two laws are self-evident; the third necessarily follows from the first and from Pascal's principle.

92. **Vertical upward pressure.**—The pressure which the upper layers of a liquid exert on the lower layers causes them to exert an equal reaction in an upward direction, a necessary consequence of the principle of transmission of pressure in all directions. This upward pressure is termed the *buoyancy* of liquids; it is very sensible when the hand is plunged into a liquid, more especially one of great density, like mercury.

The following experiment (fig. 53) serves to exhibit the upward pressure of liquids. A large open glass tube A, one end of which is ground, is fitted with a ground glass disc, O, or still better with a thin card or piece of mica, the weight of which may be neglected. To the disc is fitted a string, C, by which it can be held against the bottom of the tube. The whole is then immersed in water, and now the disc does not fall, although no longer held by the string; it is consequently kept in its position by the upward pressure of the water. If water be now slowly poured into the tube, the disc will only sink when the height of the water inside the tube is equal to the height outside. It follows thence that the upward pressure on the disc is equal to the pressure of a column of water, the base of which is the internal section of the tube A, and the height the distance from the disc to the outer surface of the liquid. Hence the *upward pressure of liquids at any point is governed by the same laws as the downward pressure.*

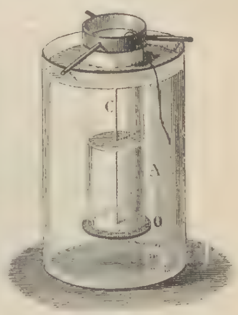


Fig. 53.

93. **Pressure is independent of the shape of the vessel.**—The pressure exerted by a liquid, in virtue of its weight, on any portion of the liquid, or on the sides of the vessel in which it is contained, depends on the depth and density of the liquid, but *is independent of the shape of the vessel and of the quantity of the liquid.*

This principle, which follows from the law of the equality of pressure, may be experimentally demonstrated by many forms of apparatus. The following is the one most frequently used, and is due to Haldat. It consists of a bent tube, ABC (fig. 54), at one end of which, A, is fitted a stop-cock, in which can be screwed two vessels, M and P, of the same height, but different in shape and capacity, the first being conical, and the other nearly cylindrical. Mercury is poured into the tube, ABC, until its level nearly reaches A. The vessel M is then screwed on and filled with water. The pressure of the water acting on the mercury

causes it to rise in the tube C, and its height may be marked by means of a little collar, *a*, which slides up and down the tube. The level of the water in M is also marked by means of the moveable rod *o*. When this is done M is then emptied by means of the stop-cock, unscrewed and replaced by P. When water is now poured in this, the mercury, which had resumed its original level in the tube ABC, again rises in C, and when the water in P has the same height as it had in M, which is indi-

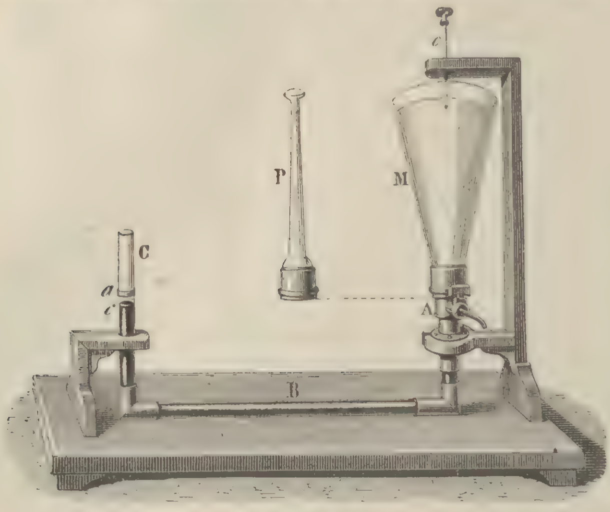


Fig. 54.

cated by the rod *o*, the mercury will have risen to the height it had before, which is marked by the collar *a*. Hence the pressure on the mercury in both cases is the same. This pressure is therefore independent of the shape of the vessels, and, consequently, also of the quantity of liquid. The base of the vessel is obviously the same in both cases ; it is the surface of the mercury in the interior of the tube A.

Another mode of demonstrating this principle is by means of an apparatus devised by Masson. In this (fig. 55) the pressure of the water contained in the vessel M is not exerted upon the column of mercury, as in that of Haldat, but on a small disc or stop *a*, which closes a tubulure *c*, on which is screwed the vessel M. The disc is not fixed to the tubulure, but is sustained by a thread attached to the end of a scale-beam. At the other end is a pan in which weights can be placed until they counterbalance the pressure exerted by the water on the stop. The vessel M being emptied is unscrewed, and replaced by the narrow tube O. This being filled to the same height as the large vessel, which is observed by means of the mark *o*, it will be observed that to keep the disc in its place just the same weight must be placed in the pan as before, which leads, therefore, to the same conclusion as does Haldat's experiment. The

same result is obtained if instead of the vertical tube P, the oblique tube Q be screwed to the tubulure.

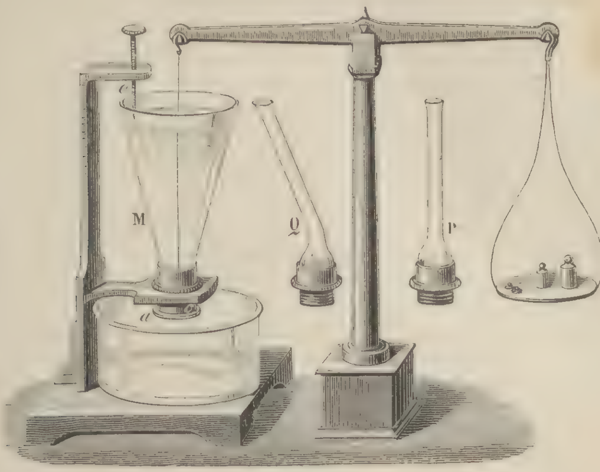


Fig. 55.

From a consideration of these principles it will be readily seen that a very small quantity of water can produce considerable pressures. Let us imagine any vessel, a cask, for example, filled with water and with a long narrow tube tightly fitted into the side. If water is poured into the tube, there will be a pressure on the bottom of the cask equal to the weight of a column of water whose base is the bottom itself, and whose height is equal to that of the water in the tube. The pressure may be made as great as we please; by means of a narrow thread of water forty feet high, Pascal succeeded in bursting a very solidly constructed cask.

The toy known as the *hydrostatic bellows* depends on the same principle, and we shall presently see a most important application of it in the hydraulic press.

From the principle just laid down, the pressures produced at the bottom of the sea may be calculated. It will be presently demonstrated that the pressure of the atmosphere is equal to that of a column of seawater about thirty-three feet high. At sea the lead has frequently descended to a depth of thirteen thousand feet; at the bottom of some seas, therefore, there must be a pressure of four hundred atmospheres.

94. **Pressure on the sides of vessels.**—Since the pressure caused by gravity in the mass of a liquid is transmitted in every direction, according to the general law of the transmission of fluid pressure, it follows that at every point of the side of any vessel a pressure is exerted, at right angles to the side, which we will suppose to be plane. The resultant of all these

pressures is the total pressure on the sides. But since these pressures increase in proportion to the depth, and also in proportion to the horizontal extent of the side, their resultant can only be obtained by calculation, which shows that the total pressure on any given portion of the side *is equal to the weight of a column of liquid, which has this portion of the side for its base, and whose height is the vertical distance from the centre of gravity of the portion to the surface of the liquid.* If the side of a vessel is a curved surface the same rule gives the pressure on the surface, but the total pressure is no longer the resultant of the fluid pressures.

The point in the side supposed plane at which the resultant of all the pressure is applied is called the *centre of pressure*, and is always below the centre of gravity of the side. For if the pressures exerted at different parts of the plane side were equal, the point of application of their resultant, the centre of pressure, would obviously coincide with the centre of gravity of the side. But since the pressures increase with the depth, the centre of pressure is necessarily below the centre of gravity. This point is determined by calculation, which leads to the following results:

i. With a rectangular side whose upper edge is level with the water, the centre of pressure is at two-thirds of the line which joins the middle of the horizontal sides measured from the top.

ii. With a triangular side whose base is horizontal, and coincident with the level of the water, the centre of pressure is at the middle of the line which joins the vertex of the triangle with the middle of the base.

iii. With a triangular side whose vertex is level with the water, the centre of pressure is in the line joining the vertex and the middle of the base, and at three-fourths of the distance of the latter from the vertex.

95. **Hydrostatic paradox.**—We have already seen that the pressure on the bottom of a vessel depends neither on the form of the vessel nor on the quantity of the liquid, but simply on the height of the liquid above the bottom. But the pressure thus exerted must not be confounded with the pressure which the vessel itself exerts on the body which supports it. The latter is always equal to the combined weight of the liquid and the vessel in which it is contained, while the former may be either smaller or greater than this weight, according to the form of the vessel. This fact is usually termed the *hydrostatic paradox*, because at first sight it appears paradoxical.

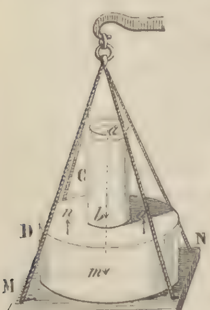


Fig. 56.

CD (fig. 56) is a vessel composed of two cylindrical parts of unequal diameters, and filled with water to *a*. From what has been said before, the bottom of the vessel CD supports the same pressure as if its diameter were everywhere the same as that of its lower part; and it would at first sight seem that the scale MN of the balance, in which the vessel CD is placed, ought to show the same weight as if there had been placed in it a cylindrical vessel having the same height of water, and having the diameter of the part D. But the pressure exerted

on the bottom of the vessel is not all transmitted to the scale MN; for the *upward* pressure upon the surface *no* of the vessel is precisely equal to the weight of the *extra* quantity of water which a cylindrical vessel would contain, and balances an equal portion of the *downward* pressure on *m*. Consequently, the pressure on the plate MN is simply equal to the weight of the vessel CD and of the water which it contains.

CONDITIONS OF THE EQUILIBRIUM OF LIQUIDS.

96. **Equilibrium of a liquid in a single vessel.**—In order that a liquid may remain at rest in a vessel of any given form, it must satisfy the two following conditions:—

I. *Its surface must be, everywhere, perpendicular to the resultant of the forces which act on the molecules of the liquid.*

II. *Every molecule of the mass of the liquid must be subject in every direction to equal and contrary pressures.*

The second condition is self-evident; for if, in two opposite directions, the pressures exerted on any given molecule were not equal and contrary, the molecule would be moved in the direction of the greater pressure, and there would be no equilibrium. Thus the second condition follows from the principle of the equality of pressures, and from the reaction which all pressure causes on the mass of liquids.

To prove the first condition, let us suppose that *mp* is the resultant of all the forces acting upon any molecule *m* on the surface (fig. 57), and that this surface is inclined in reference to the force *mp*. The latter can consequently be decomposed into two forces, *mq* and *mf*; the one perpendicular to the surface of the liquid and the other to the direction *mp*. Now the first force, *mq*, would be destroyed by the resistance of the liquid, while the second would move the molecule in the direction *mf*, which shows that equilibrium is impossible.

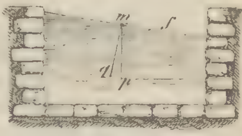


Fig. 57.

If gravity be the force acting on the liquid, the direction *mp* is vertical; hence, if the liquid is contained in a basin or vessel of small extent, the surface ought to be plane and horizontal (59), because then the direction of gravity is the same in every point. But the case is different with liquid surfaces of greater extent, like the ocean. The surface will be perpendicular to the direction of gravity; but as this changes from one point to another, and always tends towards a point near the centre of the earth, it follows that the direction of the surface of the ocean will change also, and assume a nearly spherical form.

97. **Equilibrium of the same liquid in several communicating vessels.**—When several vessels of any given form communicate with each other, there will be equilibrium when the liquid in each vessel satisfies the two preceding conditions (96), and further, *when the surfaces of the liquids in all the vessels are in the same horizontal plane.*

In the vessels ABCD (fig. 58), which communicate with each other,

let us consider any transverse section of the tube *mn*; the liquid can only remain in equilibrium as long as the pressures which this section supports from *m* in the direction of *n*, and from *n* in the direction of *m*, are equal and opposite. Now it has been already proved that these pressures are respectively equal to the weight of a column of water, whose base is the supposed section, and whose height is the distance from the centre of gravity of this section to the surface of the liquid. If we conceive, then, a horizontal plane, *mn*, drawn through the centre of gravity of this section, it will be seen that there will only be equilibrium as long as the height of the liquid above this plane is the same in each vessel, which demonstrates the principle enunciated.

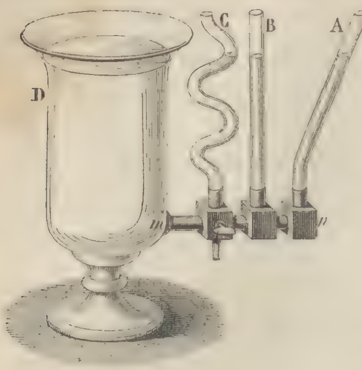


Fig. 58.

98. **Equilibrium of superposed liquids.**—In order that there should be equilibrium when several heterogeneous liquids are superposed in the same vessel, each of them must satisfy the conditions necessary for a single liquid (96); and further, *there will be stable equilibrium only when the liquids are arranged in the order of their decreasing densities from the bottom upwards.*

The last condition is experimentally demonstrated by means of the *phial of four elements.* It consists of a long narrow bottle containing mercury, water saturated with carbonate of potass, alcohol coloured red, and naphtha. When the phial is shaken the liquids mix, but when it is allowed to rest they separate; the mercury sinks to the bottom, then comes the water, then the alcohol, and then the naphtha. This is the order of the decreasing densities of the bodies. The water is saturated with carbonate of potass to prevent its mixing with the alcohol.

This separation of the liquids is due to the same cause as that which enables solid bodies to float on the surface of a liquid of greater density than their own. It is also from this principle that fresh water, at the mouths of rivers, floats for a long time on the denser salt water of the sea; and it is for the same reason that cream, which is lighter than milk, rises to the surface.

99. **Equilibrium of two different liquids in communicating vessels.**—When two liquids of different densities, which do not mix, are contained in two communicating vessels, they will be in equilibrium when, in addition to the preceding principles, they are subject to the following: *that the heights above the horizontal surface of contact of two columns of liquid in equilibrium are in the inverse ratio of their densities.*

To show this experimentally, mercury is poured into a bent glass tube, *mn*, fixed against an upright wooden support (fig. 59), and then water is poured into one of the legs, AB. The column of water, AB, pressing on

the mercury at B, lowers its level in the leg AB, and raises it in the other by a quantity, CD ; so that if, when equilibrium is established, we imagine a horizontal plane, BC, to pass through B, the column of water in AB will balance the column of mercury CD. If the heights of these two columns are then measured, by means of the scales, it will be found that the height of the column of water is about $13\frac{1}{2}$ times that of the height of the column of mercury. We shall presently see that the density of mercury is about $13\frac{1}{2}$ times that of water, from which it follows that the heights are inversely as the densities.

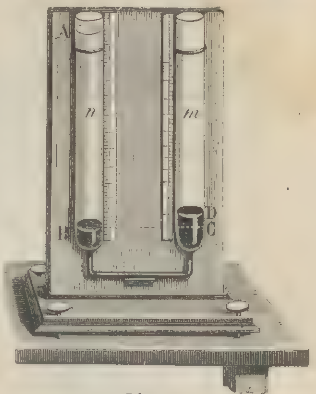


Fig. 59.

It may be added that the equilibrium cannot exist unless there is a sufficient quantity of the heavier liquid for part of it to remain in *both legs* of the tube.

The preceding principle may be deduced by a very simple calculation. Let d and d' be the densities of water and mercury, and h and h' their respective heights, and let g be the force of gravity. The pressure on B will be proportional to the density of the liquid, to its height, and to the force of gravity ; on the whole, therefore, to the product dhg. Similarly the pressure at C will be proportional to $d'h'g$. But in order to produce equilibrium, dhg must be equal to $d'h'g$, or $dh = d'h'$. This is nothing more than an algebraical expression of the above principle ; for since the two products must always be equal, d' must be as many times greater than d, as h' is less than h.

In this manner the density of a liquid may be calculated. Suppose one of the branches contained water and the other oil, and their heights were respectively 15 inches for the oil, and 14 inches for the water. The density of water being taken as unity, and that of oil being called x, we shall have

$$15 \times x = 14 \times 1 \text{ ; whence } x = \frac{14}{15} = 0{\cdot}933.$$

APPLICATIONS OF THE PRECEDING HYDROSTATIC PRINCIPLES.

100. **Hydraulic press.**—The law of the equality of pressure has received a most important application in the *hydraulic press,* a machine by which enormous pressures may be produced. Its principle is due to Pascal, but it was first constructed by Bramah in 1796.

It consists of a cylinder, B, with very strong thick sides (fig. 60), in which there is a cast iron ram, P, working water tight in the collar of the cylinder. On the ram P there is a cast iron plate on which the substance to be pressed is placed. Four strong columns serve to support and fix a second plate, Q.

By means of a leaden pipe, K, the cylinder, B, which is filled with water communicates with a small force pump, A, which works by means of a lever, M. When the piston of this pump p ascends, a vacuum is pro-

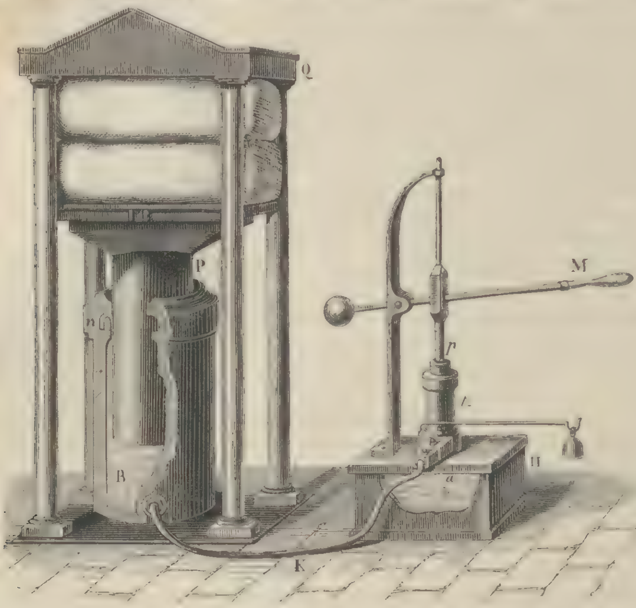


Fig. 60.

duced and the water rises in the tube a, at the end of which there is a rose, to prevent the entrance of foreign matters. When the piston p descends, it drives the water into the cylinder by the tube K.

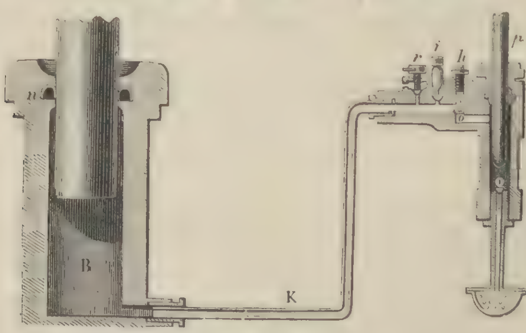


Fig. 61.

Fig. 61 represents a section, on a larger scale, of the system of valves necessary in working the apparatus. The valve o, below the piston p,

opens when the piston rises, and closes when it descends. The valve o, during this descent, is opened by the pressure of the water which passes by the pipe K. The valve i is a *safety valve*, held by a weight which acts on it by means of a lever. By weighting the latter to a greater or less extent the pressure can be regulated, for as soon as there is an upward pressure greater than that of the weight upon it, it opens and water escapes. A screw r serves to relieve the pressure, for when it is opened it affords a passage for the efflux of the water in the cylinder B.

A most important part is the leather collar n, the invention of which by Bramah removed the difficulties which had been experienced in making the large ram work water-tight when submitted to great pressures. It consists of a circular piece of stout leather, fig. 62, saturated with oil so as to be impervious to water, in the centre of which a circular hole is cut. This piece is bent, so that a section of it represents a reversed U, and is fitted into a groove n made in the neck of the cylinder. This collar being concave downwards, in proportion as the pressure increases it fits the more tightly against the ram P on one side and the neck of the cylinder on the other, and quite prevents any escape of water.

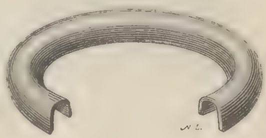


Fig. 62.

The pressure which can be obtained by this press depends on the relation of the piston P to that of the piston p. If the former has a transverse section fifty or a hundred times as large as the latter, the upward pressure on the large piston will be fifty or a hundred times that exerted upon the small one. By means of the lever M an additional advantage is obtained. If the distance from the fulcrum to the point where the power is applied is five times the distance from the fulcrum to the piston p, the pressure on p will be five times the power. Thus, if a man acts on M wiih a force of sixty pounds, the force transmitted by the piston p will be 300 pounds, and the force which tends to raise the piston P will be 30,000 pounds, supposing the section of P is a hundred times that of p.

The hydraulic press is used in all cases in which great pressures are required. It is used in pressing cloth, in extracting the juice of beet root, and in expressing oil from seeds ; it also serves to test the strength of cannon, of steam boilers, and of chain cables. The parts composing the tubular bridge which spans the Menai Straits were raised by means of an hydraulic press. The cylinder of this machine, the largest which has ever been constructed, was nine feet long and twenty-two inches in internal diameter; it was capable of raising a weight of two thousand tons.

101. **Water level.**—The *water level* is an application of the conditions of equilibrium in communicating vessels. It consists of a metal tube bent at both ends, in which are fitted glass tubes D and E (fig. 63). It is placed on a tripod, and water poured in until it rises in both legs.

When the liquid is at rest, the level of the water in both tubes is the same—that is, they are both in the same horizontal plane.

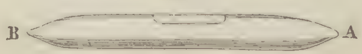
This instrument is used in levelling, or ascertaining how much one point is higher than another. If, for example, it is desired to find the difference between the heights of B and A, a *levelling-staff* is fixed on

Fig. 63.

the latter place. This staff consists of a rule formed of two sliding pieces of wood, and supporting a piece of tin plate M, in the centre of which there is a mark. This staff being held vertically at A, an observer looks at it through the level along the surfaces D and E, and directs the holder to raise or lower the slide until the mark is in the prolongation of the line DE. The height AM is then measured, and subtracting it from the height of the level, the height of the point A above B is obtained.

102. **Spirit level.**—The *spirit level* is both more delicate and more accurate than the water level. It consists of a glass tube, AB (fig. 64),

Fig. 64.



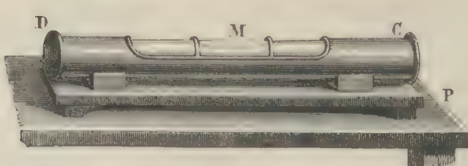


Fig. 65

very slightly curved, that is, the tube, instead of being a true cylinder as it seems to be, is in fact slightly curved in such a manner that its axis is an arc of a circle of very large radius; it is filled with spirit with the exception of a bubble of air, which tends to occupy the highest part. The tube is placed in a brass case, CD (fig. 65), which is so arranged that when it is in a perfectly horizontal position the bubble of air is exactly between the two points marked in the case.

To take levels with this apparatus, it is fixed on a telescope, which can consequently be placed in a horizontal position.

103. **Artesian wells.**—All natural collections of water exemplify the tendency of water to find its level. Thus, a group of lakes, such as the great lakes of North America, may be regarded as a number of vessels in communication, and consequently the waters tend to maintain the same level in all. This, too, is the case with the source of a river and the sea, and as the latter is on the lower level the river continually flows down to the sea along its *bed*, which is, in fact, the means of communication between the two.

Perhaps the most striking instance of this class of natural phenomena is that of *artesian wells*. These wells derive their name from the province of Artois, where it has long been customary to dig them, and from whence their use in other parts of France and Europe was derived. It seems, however, that at a very remote period wells of the same kind were dug in China and Egypt.

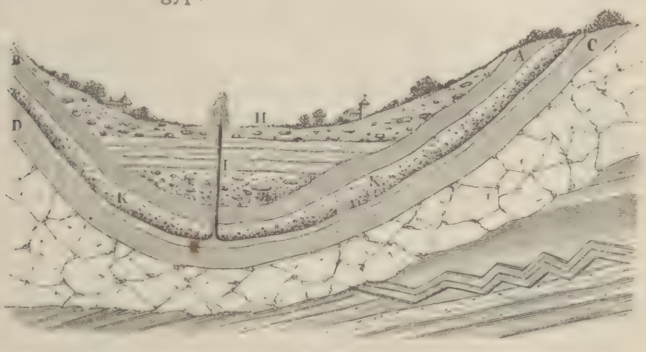


Fig. 66.

To understand the theory of these wells, it must be premised that the strata composing the earth's crust are of two kinds: the one *permeable* to water, such as sand, gravel, etc.; the others *impermeable*, such as clay. Let us suppose, then, a geographical basin of greater or less extent, in which the two impermeable layers AB, CD (fig. 66), enclose between them a permeable layer KK. The rain-water falling on the part of this layer which comes to the surface, which is called the *outcrop*, will filter through it, and following the natural fall of the ground will collect in the hollow of the basin, whence it cannot escape owing to the impermeable strata above and below it. If now a vertical hole I be sunk down to the water-bearing stratum, the water striving to regain its level will spout out to a height which depends on the difference between the levels of the outcrop and of the point at which the perforation is made.

The waters which feed artesian wells often come from a distance of sixty or seventy miles. The depth varies in different places. The well at Grenelle is 1,800 feet deep; it gives 656 gallons of water in a minute, and is one of the deepest and most abundant which have been made. The

temperature of the water is 27° C. It follows from the law of the increase of temperature with the increasing depth below the surface of the ground, that, if this well were 210 feet deeper, the water would have all the year round a temperature of 32° C., that is, the ordinary temperature of baths.

BODIES IMMERSED IN LIQUIDS.

104. **Pressure supported by a body immersed in a liquid.**—When a solid is immersed in a liquid, every portion of its surface is submitted to a perpendicular pressure, which increases with the depth. If we imagine all these pressures decomposed into horizontal and vertical pressures, the first set are in equilibrium. The vertical pressures are obviously unequal, and will tend to move the body upwards.

Let us imagine a cube immersed in a mass of water (fig. 67), and that four of its edges are vertical. The pressures upon the four vertical faces being, clearly, in equilibrium, we need only consider the pressures exerted on the horizontal faces A and B. The first is pressed downwards by a column of water, whose base is the face A, and whose height is AD, the lower face B is pressed upwards by the weight of a column of water whose base is the face itself, and whose height is BD (94). The cube, therefore, is urged upwards by a force equal to the difference between these two pressures, which latter is manifestly equal to the weight of a column of water having the same base and the same height as this cube. *Consequently this upward pressure is equal to the weight of the volume of water displaced by the immersed body.*

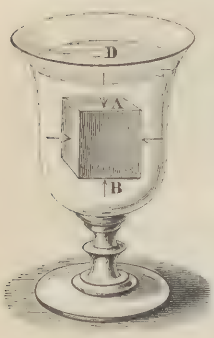


Fig. 67.

We shall readily see from the following reasoning that every body immersed in a liquid is pressed upwards by a force equal to the weight of the displaced liquid. In a liquid at rest, let us suppose a portion of it of any given shape, regular or irregular, to become solidified, without either increase or decrease of volume. The liquid thus solidified will remain at rest, and therefore must be acted upon by a force equal to its weight, and acting vertically upward through its centre of gravity; for otherwise motion would ensue. If in the place of the solidified water we imagine a solid of another substance of exactly the same volume and shape, it will necessarily receive the same pressures from the surrounding liquid as the solidified portion did; hence, like the latter, it will sustain the pressure of a force acting vertically upward through the centre of gravity of the displaced liquid, and equal to the weight of the displaced liquid. If, as almost invariably happens, the liquid is of uniform density, the centre of gravity of the displaced liquid means the centre of gravity of the immersed part of the body *supposed to be of uniform density*. This distinction is sometimes of importance; for example, if a sphere is

composed of a hemisphere of iron and another of wood, its centre of gravity would not coincide with its geometrical centre; but if it were placed under water, the centre of gravity of the displaced water would be at the geometrical centre, that is, will have the same position as the centre of gravity of the sphere, if of uniform density.

105. **Principle of Archimedes.**—The preceding principles prove that every body immersed in a liquid is submitted to the action of two forces; gravity which tends to lower it, and the buoyancy of the liquid which tends to raise it with a force equal to the weight of the liquid displaced.

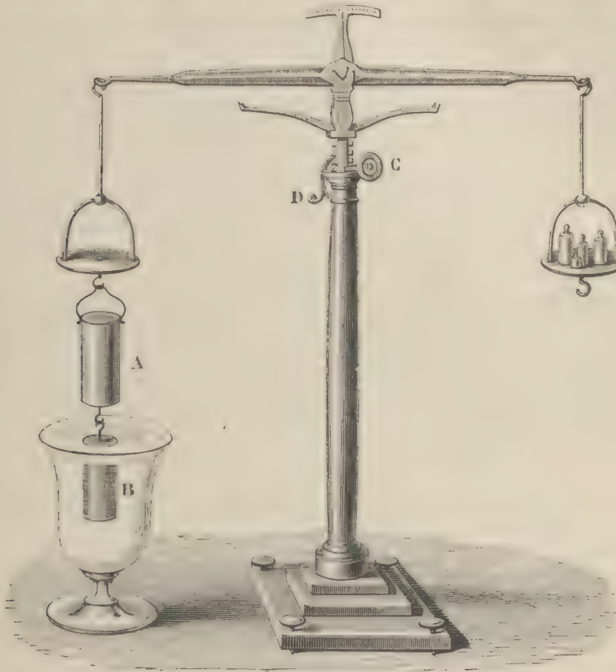


Fig. 68.

The weight of the body is either totally or partially overcome by this buoyancy, from which it is concluded that *a body immersed in a liquid loses a part of its weight equal to the weight of the displaced liquid.*

This principle, which is 'the basis of the theory' of immersed and floating bodies, is called the principle of Archimedes, after the discoverer. It is shown experimentally by means of the *hydrostatic balance* (fig. 68). This is an ordinary balance, each pan of which is provided with a hook; the beam can be raised by means of a toothed rack, which is worked by a little pinion, C. A catch, D, holds the rack when it has been raised. The beam being raised, a hollow copper cylinder, A, is suspended to one

of the pans, and below this a solid cylinder, B, whose volume is exactly equal to the capacity of the first cylinder; lastly, an equipoise is placed in the other pan. If now the hollow cylinder be filled with water the equilibrium is disturbed; but if at the same time the beam is lowered so that the solid cylinder B becomes immersed in a vessel of water placed beneath it, the equilibrium will be restored. By being immersed in water, the cylinder B loses a portion of its weight equal to that of the water in the cylinder A. Now as the capacity of the cylinder A is exactly equal to the volume of the cylinder B, the principle which has been before laid down is proved.

106. **Determination of the volume of a body.**—The principle of Archimedes furnishes a method for obtaining the volume of a body of any shape, provided it is not soluble in water. The body is suspended by a fine thread to the hydrostatic balance, and is weighed first in the air, and then in distilled water at 4°C. The loss of weight is the weight of the displaced water, from which the volume of the displaced water is readily calculated. But this volume is manifestly that of the body itself. Suppose, for example, 155 grammes is the loss of weight. This is consequently the weight of the displaced water. Now it is known that a gramme is the weight of a cubic centimeter of water at 4°; consequently, the volume of the body immersed is 155 cubic centimeters.

107. **Equilibrium of floating bodies.**—A body when floating is acted on by two forces, namely, its weight, which acts vertically downward through its centre of gravity, and the resultant of the fluid pressures, which (104) acts vertically upward through the centre of gravity of the fluid displaced; but if the body is at rest these two forces must be equal,

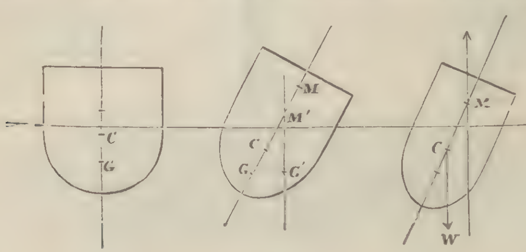


Fig. 69. Fig. 70. Fig. 71.

and act in opposite directions; whence follow the conditions of equilibrium, namely :—

i. *The floating body must displace a volume of liquid whose weight equals that of the body.*

ii. *The centre of gravity of the floating body must be in the same vertical line with that of the fluid displaced.*

Thus in fig. 69, if C is the centre of gravity of the body and G that of the displaced fluid, the line GC must be vertical, since when it is so the weight of the body and the fluid pressure will act in opposite directions along the same line, and will be in equilibrium if equal. It is convenient

with reference to the subject of the present article, to speak of the line CG produced as the axis of the body.

Next let it be enquired whether the equilibrium be stable or unstable. Suppose the body to be turned through a small angle (fig. 70) so that the axis takes a position inclined to the vertical. The centre of gravity of the displaced fluid will no longer be G but some other point G′. And since the fluid pressure acts vertically upward through G′, its direction will cut the axis in some point M′, which will generally have different positions according as the inclination of the axis to the vertical is greater or smaller. If the angle is indefinitely small, M′ will have a definite position M, which always admits of determination, and is called the *metacentre.*

If we suppose M to be above C, an inspection of fig. 71 will show that when the body has received an indefinitely small displacement the weight of the body W and the resultant of the fluid pressures R tends to bring the body back to its original position, that is, in this case the equilibrium is stable (62). If, on the contrary, M is below C, the forces tend to cause the axis to deviate farther from the vertical, and the equilibrium is unstable. Hence the rule,

iii. *The equilibrium of a floating body is stable or unstable according as the metacentre is above or below the centre of gravity.*

The determination of the metacentre can rarely be affected except by means of a somewhat difficult mathematical process. When, however, the form of the immersed part of a body is spherical it can be readily determined, for since the fluid pressure at each point converges to the centre, and continues to do so when the body is slightly displaced, their resultant must in all cases pass through the centre, which is therefore the metacentre. To illustrate this : let a spherical body float on the surface of a liquid (fig. 72), then its centre of gravity and the metacentre both coinciding with the geometrical centre C its equilibrium is neutral (62) ; now suppose a small heavy body to be fastened at P the summit of the vertical diameter. The centre of gravity will now be at some point G above C. Consequently the equilibrium is unstable, and the sphere, left to itself, will instantly turn over and will rest when P is the lower end of a vertical diameter.

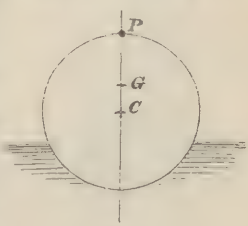


Fig. 72.

On investigating the position of the metacentre of a cylinder, it is found that when the ratio of the radius to the height is greater than a certain quantity, the position of stable equilibrium is that in which the axis is vertical ; but if it be less than that quantity, the equilibrium is stable when the axis is horizontal. For this reason the stump of a tree floats lengthwise, but a thin disc of wood floats flat on the water.

Hence, also, if it is required to make a cylinder of moderate length float with its axis vertical, it is necessary to load it at the lower end. By so doing its centre of gravity is brought below the metacentre.

The determination of the metacentre and of the centre of gravity is of great importance in the stowage of vessels, for on their relative positions the stability depends.

108. **Cartesian diver.**—The different effects of suspension, immersion, and floating are reproduced by means of a well-known hydrostatic toy, the *Cartesian diver* (fig. 73). It consists of a glass cylinder nearly full of water, on the top of which a brass cap, provided with a piston, is hermetically fitted. In the liquid there is a little porcelain figure attached to a hollow glass ball *a*, which contains air and water, and floats on the surface. In the lower part of this ball there is a little hole by which water can enter or escape, according as the air in the interior is more or less compressed. The quantity of water in the globe is such that very little more is required to make it sink. If the piston be slightly lowered the air is compressed, and this pressure is transmitted to the water of the vessel and the air in the bulb. The consequence is, that a small quantity of water penetrates into the bulb, which therefore becomes heavier and sinks. If the pressure is relieved, the air in the bulb expands, expels the excess of water which had entered it, and the apparatus being now lighter, rises to the surface. The experiment may also be made, by replacing the brass cap and piston by a cover of sheet india rubber, which is tightly tied over the mouth: when this is pressed by the hand the same effects are produced.

Fig. 73.

109. **Swimming bladder of fishes.**—Most fishes have an air-bladder below the spine, which is called the *swimming bladder*. The fish can compress or dilate this at pleasure by means of a muscular effort, and produce the same effects as those just described—that is, it can either rise or sink in water.

110. **Swimming.**—The human body is lighter, on the whole, than an equal volume of water; it consequently floats on the surface and still better in sea water, which is heavier than fresh water. The difficulty in swimming consists not so much in floating, as in keeping the head above water, so as to breathe freely. In man the head is heavier than the lower parts, and consequently tends to sink, and hence swimming is an art which requires to be learned. With quadrupeds, on the contrary, the head being less heavy than the posterior parts of the body, remains above water without any effort, and these animals therefore swim naturally.

SPECIFIC GRAVITY—HYDROMETERS.

111. **Determination of specific gravities.**—It has been already explained (24) that the specific gravity of a body, whether solid or liquid,

is the number which expresses the relation of the weight of a given volume of this body, to the weight of the same volume of distilled water at a temperature of 4°. In order, therefore, to calculate the specific gravity of a body, it is sufficient to determine its weight and that of an equal volume of water, and then to divide the first weight by the second: the quotient is the specific gravity of the body.

Three methods are commonly used in determining the specific gravities of solids and liquids. These are, 1st, the method of the hydrostatic balance; 2nd, that of the hydrometer; and 3rd, the specific gravity flask. All three, however, depend on the same principle, that of first ascertaining the weight of a body, and then that of an equal volume of water. We shall first apply these methods to determining the specific gravity of solids, and then to the specific gravity of liquids.

112. **Specific gravity of solids.**—i. *Hydrostatic balance.* To obtain the specific gravity of a solid by the hydrostatic balance (fig. 68), it is first weighed in the air, and is then suspended to the hook of the balance and weighed in water. The loss of weight which it experiences is, according to Archimedes' principle, the weight of a volume of water equal to its own volume; consequently, dividing the weight in air by the loss of weight in water, the quotient is the specific gravity required. If P is the weight of the body in air, P′ its weight in water, and D its specific gravity; P – P′ being the weight of the displaced water, we have $D = \frac{P}{P - P'}$.

It may be observed that though the weighing is performed in air, yet, strictly speaking, the quantity required is the weight of the body *in vacuo*, and when great accuracy is required, it is necessary to apply to the observed weights a correction for the weights of the unequal volumes of air displaced by the substance, and the weights in the other scale pan. It may also be remarked that the water in which bodies are weighed is, strictly speaking, distilled water at a standard temperature.

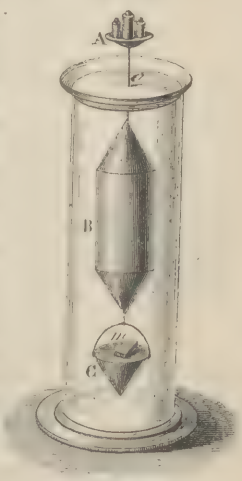


Fig. 74.

ii. *Nicholson's hydrometer.*—This apparatus consists of a hollow metallic cylinder B (fig. 74), to which is fixed a cone C, loaded with lead. The object of the latter is to bring the centre of gravity below the metacentre, so that the cylinder may float with its axis vertical. At the top is a stem, terminated by a pan, in which is placed the substance whose specific gravity is to be determined. On the stem a standard point, *o*, is marked.

The apparatus stands partly out of the water, and the first step is to ascertain the weight which must be placed in the pan in order to make the hydrometer sink to the standard point *o*. Let

this weight be 125 grains, and let sulphur be the substance whose specific gravity is to be determined. The weights are then removed from the pan, and replaced by a piece of sulphur which weighs less than 125 grains, and weights added until the hydrometer is again depressed to the standard *o*. If, for instance, it has been necessary to add 55 grains, the weight of the sulphur is evidently the difference between 125 and 55 grains, that is, 70 grains. Having thus determined the weight of the sulphur in air, it is now only necessary to ascertain the weight of an equal volume of water. To do this, the piece of sulphur is placed in the lower pan C at *m*, as represented in the figure. The whole weight is not changed, nevertheless the hydrometer no longer sinks to the standard ; the sulphur, by immersion, has lost a part of its weight equal to that of the water displaced. Weights are added to the upper pan until the hydrometer sinks again to the standard. This weight, 34·4 grains, for example, represents the weight of the volume of water displaced ; that is, of the volume of water equal to the volume of the sulphur. It is only necessary, therefore, to divide 70 grains, the weight in air, by 34·4 grains, and the quotient 2·03 is the specific gravity.

If the body in question is lighter than water it tends to rise to the surface, and will not remain on the lower pan C. To obviate this, a small moveable cage of fine wire is adjusted so as to prevent the ascent of the body. The experiment is in other respects the same.

113. **Specific gravity flask.**—When the specific gravity of a substance in a state of powder is required, it can be found most conveniently by means of the specific gravity flask. This instrument is a small flask with a large neck fitted with a carefully ground glass stopper (fig. 75). The stopper is perforated along its axis, and the bore is continued by means of a thin tube which expands into a tube of greater diameter, as shown in the figure. On the thin tube is a mark *a*, and at each weighing the flask is filled with water exactly to the mark. This is done by filling the flask when wholly under water, and putting in the stopper while it is immersed. The flask and the tube are then completely filled, and the quantity of water in excess is removed by blotting paper. To find the specific gravity proceed as follows: Having weighed the powder, place it in one of the scale pans, and with it the flask filled exactly to *a* and carefully dried. Then balance it by placing small shot, or sand, in the other pan. Next, remove the flask and pour the powder into it, and, as before, fill it up with water to the mark *a*. On replacing the flask in the scale pan it will no longer balance the shot, since the powder has displaced a volume of water equal to its own volume. Place weights in the scale pan along with the flask until they balance the shot. These weights give the weight of the water displaced. Then the weight of the powder, and the weight of an equal bulk of water being known, its specific gravity is determined as before.

Fig. 75.

It is important in this determination to remove the layer of air which

adheres to the powder, and unduly increases the quantity of water expelled. This is effected by placing the bottle under the receiver of an air pump, and exhausting. The same result is obtained by boiling the water in which the powder is placed.

114. **Bodies soluble in water.**—If the body, whose specific gravity is to be determined by any of these methods, is soluble in water, the determination is made in some liquid in which it is not soluble, such as oil, turpentine, or naphtha, the specific gravity of which is known. The specific gravity is obtained by multiplying the number obtained in this experiment by the specific gravity of the liquid used for the determination.

Suppose, for example, a determination of the specific gravity of potassium has been made in naphtha. For equal volumes, P represents the weight of the potassium, P′ that of the naphtha, and P″ that of water; consequently $\frac{P}{P'}$ will be the specific gravity of the substance in reference to naphtha, and $\frac{P'}{P''}$ the specific gravity of the naphtha in reference to water. The product of these two fractions $\frac{P}{P''}$ is the specific gravity of the substance compared with water.

In determining the specific gravity of porous substances, they are varnished before being immersed in water, which renders them impervious to moisture without altering their volume.

Specific gravity of solids at zero as compared with distilled water at 4° C.

Platinum, rolled	22·069	Statuary marble	2·837
„ cast	20·337	Aluminium	2·680
Gold, stamped	19·362	Rock crystal	2·653
„ cast	19·258	St. Gobin glass	2·488
Lead, cast	11·352	China porcelain	2·385
Silver, cast	10·474	St. Sèvres porcelain	2·146
Bismuth, cast	9·822	Native sulphur	2·033
Copper, drawn wire	8·878	Ivory	1·917
„ cast	8·788	Anthracite	1·800
Brass	8.383	Compact coal	1·329
Steel, not hammered	7·816	Amber	1·078
Iron, bar	7·788	Melting ice	0·930
Iron, cast	7·207	Beech	0·852
Tin, cast	7·291	Oak	0·845
Zinc, cast	6·861	Elm	0·800
Antimony, cast	6·712	Yellow pine	0·657
Diamonds	3·531 to 3·501	Common poplar	0·389
Flint glass	3·329	Cork	0·240

115. **Specific gravity of liquids.**—i. *Method of the hydrostatic balance.* From the plan of the hydrostatic balance a body is suspended, on which the liquid whose specific gravity is to be determined, exerts no chemical

action; for example, a ball of platinum. This is then successively weighed in air, in distilled water, and in the liquid. The loss of weight of the body in these two liquids is noted. They represent respectively the weights of equal volumes of water and of the given liquid, and consequently it is only necessary to divide the second of them by the first to obtain the required specific gravity.

Let P be the weight of the platinum ball in air, P′ its weight in water, P″ its weight in the given liquid, and let D be the specific gravity sought. The weight of the water displaced by the platinum is $P - P'$ and that of the second liquid is $P - P''$, from which we get $D = \frac{P - P''}{P - P'}$.

ii. *Fahrenheit's hydrometer.*—This instrument (fig. 76) resembles Nicholson's hydrometer, but it is made of glass, so as to be used in all liquids. At its lower extremity, instead of a pan, it is loaded with a small bulb containing mercury. There is a standard mark on the stem.

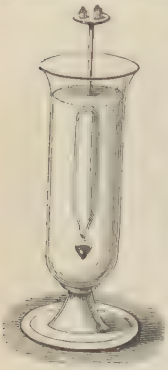


Fig. 76.

The weight of the instrument is first accurately determined in air; it is then placed in water, and weights added to the scale pan until the mark on the stem is level with the water. It follows from the first principle of the equilibrium of floating bodies, that the weight of the hydrometer, together with the weight in the scale pan, is equal to the weight of the volume of the displaced water. In the same manner, the weight of an equal volume of the given liquid is determined, and the specific gravity is found by dividing the latter weight by the former.

Neither Fahrenheit's nor Nicholson's hydrometers give such accurate results as the hydrostatic balance.

iii. *Specific gravity flask.*—This has been already described. In determining the specific gravity of a liquid, the flask is first weighed empty, and then successively, full of water, and of the given liquid. If the weight of the flask be subtracted from the two weights thus obtained, the result represents the weights of equal volumes of the liquid and of water, from which the specific gravity is obtained by division.

116. **On the observation of temperature in ascertaining specific gravities.**—As the volume of a body increases with the temperature, and as this increase varies with different substances, the specific gravity of any given body is not exactly the same at different temperatures; and, consequently, a certain fixed temperature is chosen for these determinations. That of water, for example, has been made at 4° C., for at this point it has the greatest density. The specific gravities of other bodies are assumed to be taken at zero; but as this is not always possible, certain corrections must be made, which we shall consider in the Book on Heat.

Specific gravities of liquids at zero, compared with that of water at 4° C. *as unity.*

Mercury	13·598	Distilled water at 4° C.	1·000
Bromine	2·960	„ „ at 0° C.	0·999
Sulphuric acid	1·841	Claret	0·994
Nitric acid	1·420	Olive oil	0·915
Hydrochloric acid	1·240	Oil of turpentine	0·870
Blood	1·060	Naphtha	0·847
Milk	1·032	Absolute alcohol	0·803
Sea water	1·026	Ether	0·723

117. **Use of tables of specific gravity.**—Tables of specific gravity admit of numerous applications. In mineralogy the specific gravity of a mineral is often a highly distinctive character. By means of tables of specific gravities the weight of a body may be calculated when its volume is known, and conversely the volume when its weight is known.

With a view to explaining the last-mentioned use of these tables, it will be well to premise a statement of the connection existing between the British units of length, capacity, and weight. It will manifestly be sufficient for this purpose to define that which exists between the yard, gallon, and pound avoirdupois, since other measures stand to these in well-known relations. The yard, consisting of 36 inches, may be regarded as the primary unit. Though it is essentially an arbitrary standard, it is determined by this, that the simple pendulum which makes an oscillation, in a mean second at London on the sea level, is 39·1375 inches long. The gallon contains 277·274 cubic inches. A gallon of distilled water at the standard temperature weighs 10 lbs. avoirdupois or 70,000 grains troy; or, which comes to the same thing, one cubic inch of water weighs 252·5 grains.

On the French system the meter is the primary unit, and is so chosen that 10,000,000 meters are the length of a quadrant of the meridian from either pole to the equator. The meter contains 10 decimeters, or 100 centimeters, or 1,000 millimeters, its length equals 1·0936 yards. The unit of the measure of capacity is the litre or cubic decimeter. The unit of weight is the gramme, which is the weight of a cubic centimeter of distilled water at 4° C. The kilogramme contains 1,000 grammes, or is the weight of a decimeter of distilled water at 4° C. The gramme equals 15·443.

If V is the number of cubic centimeters (or decimeters) in a certain quantity of distilled water at 4° C., and P its weight in grammes (or kilogrammes), it is plain that $P = V$. Now consider a substance whose specific gravity is D, every cubic centimeter of this substance will weigh as much as D cubic centimeters of water, and therefore V centimeters of this substance will weigh as much as DV centimeters of water. Hence if P is the weight of the substance in grammes we have $P = DV$. If, however, V is the volume in cubic inches, and P the weight in grains, we shall have $P = 252·5\ DV$.

As an example, we may calculate the internal diameter of a glass tube.

Mercury is introduced, and the length and weight of the column at 4° C. are accurately determined. As the column is cylindrical, we have $V = \pi r^2 l$, where r is the radius, and l the length of the column in centimeters. Hence if D is the specific gravity of mercury, and P the weight of the column in grammes, we have $P = \pi r^2 l D$, and therefore

$$r = \sqrt{\frac{P}{\pi D l}}$$

If r and l are in inches and P in grains, we shall have $P = 252{\cdot}5 \pi r^2 l D$, and therefore

$$r = \sqrt{\frac{P}{252{\cdot}5\pi 5 D l}}$$

In a similar manner the diameter of very fine metallic wires can be calculated.

118. **Hydrometers with variable volume.**—The hydrometers of Nicholson and Fahrenheit are called *hydrometers of constant volume, but variable weight*, because they are always immersed to the same extent, but carry different weights. There are also *hydrometers of variable volume but of constant weight.* These instruments, known under the different names of *acidometer, alcoholometer, lactometer, and saccharometer*, are not used to determine the specific gravity of the liquids, but to show whether the acids, alcohols, solutions of sugar, etc., are more or less concentrated.

119. **Beaumé's hydrometer.**—This, which was the first of these instruments, may serve as a type of them. It consists of a glass tube (fig. 77) loaded at its lower end with mercury, and with a bulb blown in the middle. The stem, the external diameter of which is as regular as possible, is hollow, and the scale is marked upon it.

The graduation of the instrument differs according as the liquid, for which it is to be used, is heavier or lighter than water. In the first case, it is so constructed that it sinks in water nearly to the top of the stem, to a point A, which is marked zero. A solution of fifteen parts of salt in eighty-five parts of water is made, and the instrument immersed in it. It sinks to a certain point on the stem, B, which is marked 15; the distance between A and B is divided into 15 equal parts, and the graduation continued to the bottom of the stem. Sometimes the graduation is on a piece of paper in the interior of the stem.

Fig. 77.

The hydrometer thus graduated only serves for liquids of a greater specific gravity than water, such as acids and saline solutions. For liquids lighter than water a different plan must be adopted. Beaumé took for zero the point to which the apparatus sank in a solution of 10 parts of salt in 90 of water, and for 10° he took the level in distilled water. This distance he divided into 10°, and continued the division to the top of the scale.

The graduation of these hydrometers is entirely conventional, and they give neither the densities of the liquids, nor the quantities dissolved. But they are very useful in making mixtures or solutions in given proportions, the results they give being sufficiently near in the majority of cases. For instance, it is found that a well-made syrup marks 35° on Beaumé's hydrometer, from which a manufacturer can readily judge whether a syrup which is being evaporated has reached the proper degree of concentration.

120. **Gay-Lussac's alcoholometer.** — This instrument is used to determine the strength of spirituous liquors ; that is, the proportion of pure alcohol which they contain. It differs from Beaumé's hydrometer in a graduation.

Mixtures of absolute alcohol and distilled water are made, containing 5, 10, 20, 30, etc., per cent. of the former. The alcoholometer is so constructed that, when placed in pure distilled water, the bottom of its stem is level with the water, and this point is zero. It is next placed in absolute alcohol, which marks 100°, and then successively in mixtures of different strengths, containing 10, 20, 30, etc., per cent. The divisions thus obtained are not exactly equal, but their difference is not great, and they are subdivided into ten divisions, each of which marks *one* per cent. of absolute alcohol in a liquid. Thus a brandy in which the alcoholometer stood at 48, would contain 48 per cent. of absolute alcohol, and the rest would be water.

All these determinations are made at 15° C., and for that temperature only are the indications correct. For, other things being the same, if the temperature rises the liquid expands, and the alcoholometer will sink, and the contrary, if the temperature falls. To obviate this error Gay-Lussac constructed a table which for each percentage of alcohol gives the reading of the instrument for each degree of temperature from 0° up to 30°. When the exact analysis of an alcoholic mixture is to be made, the temperature of the liquid is first determined, and then the point to which the alcoholometer sinks in it. The number in the table corresponding to these data indicates the percentage of alcohol. From its giving the percentage of alcohol, this is often called the *centesimal alcoholometer.*

121. **Salimeters.**—*Salimeters*, or instruments for indicating the percentage of salt contained in a solution, are made on the principle of the centesimal alcoholometer. They are graduated by immersing them in pure water, which gives the zero, and then in solutions containing different percentages, 5, 10, 20, etc., of the salt, and marking on the scale the corresponding points. These instruments are so far objectionable, that every salt requires a special instrument. Thus one graduated for common salt would give totally false indications in a solution of nitre.

Lactometers and *vinometers* are similar instruments, and are used for measuring the quantity of water which is introduced into milk or wine for the purpose of adulteration. But their use is limited, because the density of these liquid is very variable, even when they are perfectly natural, and an apparent fraud may be really due to a bad natural quality of wine

or milk. *Urinometers*, which are of extensive use in medicine, are based on the same principle.

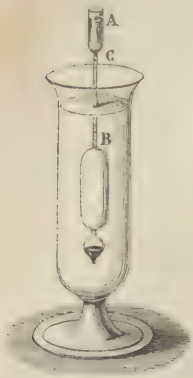


Fig. 78.

122. **Densimeter.**—The *densimeter* is an apparatus for indicating the specific gravity of a liquid. Gay-Lussac's densimeter has the same construction as Beaumé's hydrometer, but is graduated in a different manner. Rousseau's densimeter (fig. 78) is of great use in many scientific investigations, in determining the specific gravity of a small quantity of a liquid. It has the same form as Beaumé's hydrometer, but on the upper part of the stem there is a small tube, in which is placed the substance to be determined. A mark on the side of the tube indicates a measure of a cubic centimeter.

The instrument is so constructed that it sinks in distilled water to a point, B, just at the bottom of the stem. It is then filled with distilled water to the height measured on the tube, which indicates a cubic centimeter, and the point to which it now sinks is 20°. The interval between 0 and 20 is divided into 20 equal parts, and this graduation is continued to the top of the scale. As this is of uniform bore each division corresponds to $\frac{1}{20}$ gramme or 0·05.

To obtain the density of any liquid, bile for example, the tube is filled with it up to the mark A; if the densimeter sinks to $20\frac{1}{2}$ divisions, its weight is $0·05 \times 20·5 = 1·025$; that is to say, that with equal volumes the weight of water being 1, that of bile is 1·025. The specific gravity of bile is therefore 1·025.

CHAPTER II.

CAPILLARITY, ENDOSMOSE, EFFUSION, ABSORPTION, AND IMBIBITION.

123. **Capillary phenomena.**—When solid bodies are placed in contact with liquids, a class of phenomena is produced called *capillary phenomena*, because they are best seen in tubes whose diameters are comparable with the diameter of a hair. These phenomena are treated of in physics under the head of *capillarity* or *capillary attraction*: the latter expression is also applied to the force which produces the phenomena.

The phenomena of capillarity are very various, but may all be referred to the mutual attraction of the liquid molecules for each other, and to the attraction between these molecules and solid bodies. The following are some of these phenomena:—

When a body is placed in a liquid which wets it, for example a glass rod in water, the liquid, as if not subject to the laws of gravitation, is raised upwards against the sides of the solid, and its surface, instead of

being horizontal, becomes slightly concave (fig. 79). If, on the contrary, the solid is one which is not moistened by the liquid, as glass by mercury, the liquid is depressed against the sides of the solid, and assumes a convex shape, as represented in fig. 80. The surface of the liquid exhibits the same concavity or convexity against the sides of a vessel in which it is contained, according as the sides are or are not moistened by the liquid.

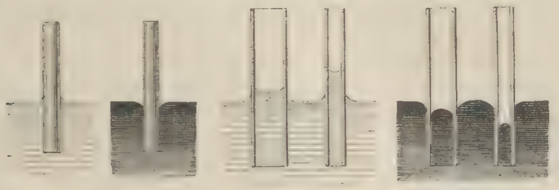


Fig. 79. Fig. 80. Fig. 81. Fig. 82.

These phenomena are much more apparent when a tube of small diameter is placed in a liquid. And according as the tubes are or are not moistened by the liquid, an ascent or a depression of the liquid is produced, which is greater in proportion as the diameter is less (figs. 81 and 82).

When the tubes are moistened by the liquid, its surface assumes the form of a concave hemispherical segment, called the *concave meniscus* (fig. 81); when the tubes are not moistened, there is *convex meniscus* (fig. 82).

124. **Laws of the ascent and depression in capillary tubes.**—Gay-Lussac has shown experimentally that the elevation and depression of liquids in capillary tubes are governed by the three following laws:—

I. *When a capillary tube is placed in a liquid, the liquid is raised or depressed according as it does or does not moisten the tube.*

II. *For the same liquid the elevation varies inversely as the diameter of the tube, when the diameter does not exceed two millimeters.*

III. *The elevation varies with the nature of the liquid, and with the temperature, but is independent of the nature and thickness of the tube.*

These laws hold good in vacuo as well as in air.

When liquids are in tubes which they do not moisten, the depression is in the inverse ratio of the diameter of the tubes; but for tubes of the same diameter the depression depends on the substance of the tubes. For instance, in an iron tube 1 millimeter in diameter, the depression of mercury is 1·226 millimeter; but in a platinum tube of the same diameter the depression is 0·655 millimeter. Moreover the depression depends on the height of the convex meniscus of the mercury, and this height varies for the same tube, according as the meniscus is formed during an ascending or descending motion of the mercurial column in the tube. These results undergo modification if the mercury is impure.

125. **Ascent and depression between parallel or inclined surfaces.**—When two bodies of any given shape are dipped in water, analogous capillary phenomena are produced, provided the bodies are sufficiently near. If, for example, two parallel glass plates are immersed in water,

at a very small distance from each other, water will rise between the two plates in the inverse ratio of the distance which separates them. The height of the ascent for any given distance is half what it would be in a tube whose diameter is equal to the distance between the plates.

If the parallel plates are immersed in mercury, a corresponding depression is produced, subject to the same laws.

If two glass plates AB and AC with their planes vertical and inclined to one another at a small angle, as represented in fig. 83, have their ends dipped into a liquid which wets them, the liquid will rise between them. The elevation will be greatest at the line of contact of plates and from thence gradually less, the surface taking the form of an equilateral hyperbola, whose asymptotes are respectively the line of intersection of the plates, and the line in which the plates cut the horizontal surface of the water.

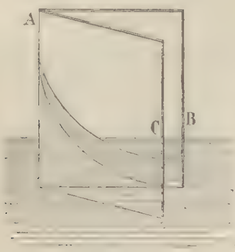


Fig. 83.

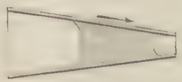


Fig. 84.

Fig. 85.

If a drop of water be placed within a conical glass tube whose angle is small and axis horizontal it will have a concave meniscus at each end (fig. 84), and will tend to move towards the vertex. But if the drop be of mercury it will have a convex meniscus at each end (fig. 85) and will tend to move from the vertex.

126. **Attraction and repulsion produced by capillarity.**—The attractions and repulsions observed between bodies floating on the surface of liquids are due to capillarity, and are subject to the following laws :—

i. When two floating balls both moistened by the liquid, for example, cork upon water, are so near that the liquid surface between them is not level, an attraction takes place.

ii. The same effect is produced when neither of the balls is moistened, as is the case with balls of wax on water.

iii. Lastly, if one of the balls is moistened and the other not, as a ball of cork and a ball of wax in water, they repel each other if the curved surfaces of the liquid in their respective neighbourhoods intersect.

As all these capillary phenomena depend on the concave or convex curvature which the liquid assumes in contact with the solid, a short explanation of the cause which determines the form of this curvature is necessary.

127. **Cause of the curvature of liquid surfaces in contact with solids.**—The form of the surface of a liquid in contact with a solid

depends on the relation between the attraction of the solid for the liquid, and of the mutual attraction between the molecules of the liquid.

Let *m* be a liquid molecule (fig. 86) in contact with a solid. This molecule is acted upon by three forces: by gravity, which attracts it in the direction of the vertical *m*P; by the attraction of the liquid F, which acts in the direction *m*F; and by the attraction of the plate *n*, which is exerted in the direction *mn*. According to the relative intensities of these forces, their resultant can take three positions :—

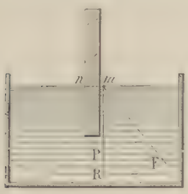


Fig. 86.

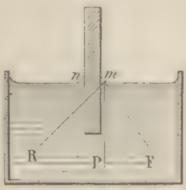


Fig. 87.

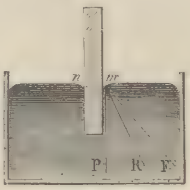


Fig. 88.

i. The resultant is in the direction of the vertical *m*R (fig. 86). In this case the surface *m* is plane and horizontal; for, from the condition of the equilibrium of liquids, the surface must be perpendicular to the force which acts upon the molecules.

ii. If the force *n* increases or F diminishes, the resultant R is within the angle *nm*P (fig. 87): in this case the surface takes a direction perpendicular to *m*R, and becomes concave.

iii. If the force F increases, or *n* diminishes, the resultant R takes the direction *m*R (fig. 88) within the angle P*m*F, and the surface becoming perpendicular to this direction is convex.

128. **Influence of the curvature on capillary phenomena.**—The elevation or depression of a liquid in a capillary tube depends on the concavity or convexity of the meniscus. In a concave meniscus, *abcd* (fig. 89), the liquid molecules are sustained in equilibrium by the forces acting on them, and they exercise no downward pressure on the inferior

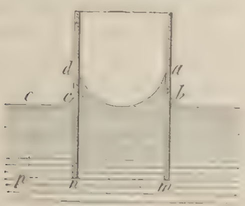


Fig. 89.

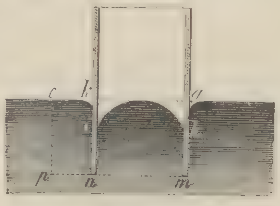


Fig. 90.

layers. On the contrary, in virtue of the molecular attraction, they act on the nearest inferior layers, from which it follows that the pressure on any layer, *mn*, in the interior of the tube, is less than if there were no meniscus. The consequence is, that the liquid ought to rise in the tube

until the internal pressure on the layer, *mn*, is equal to the pressure, *op*, which acts externally on a point, *p*, of the same layer.

Where the meniscus is convex (fig. 90) equilibrium exists in virtue of the molecular forces acting on the liquid; but as the molecules which would occupy the space *ghik*, if there were no molecular action, do not exist, they exercise no attraction on the lower layers. Consequently the pressure on any layer *mn*, in the interior of the tube, is greater than if the space *ghik* were filled, for the molecular forces are more powerful than gravity. The liquid ought, therefore, to sink in the tube until the internal pressure on a layer, *mn*, is equal to the external pressure on any point, *p*, of this layer.

The theory of capillarity, one of the most difficult in physics, can only be treated completely by mathematical analysis. It has engaged the attention of the most eminent mathematicians, particularly Clairaut, Laplace, and Poisson. As we have seen, the theory accounts for the elevation and depression of liquids not only in tubes, but also between parallel and inclined plates. It also explains the attractions and repulsions observed between floating bodies.

129. **Various capillary phenomena.**—The following facts are among the many which are caused by capillarity:—

When a capillary tube is immersed in a liquid which moistens it, and is then carefully removed, the column of liquid in the tube is seen to be longer than while the tube was immersed in the liquid. This arises from the fact that a drop adheres to the lower extremity of the tube, and forms a concave meniscus, which concurs with that of the upper meniscus to form a longer column (128).

For the same reason a liquid does not overflow in a capillary tube, although the latter may be shorter than the liquid column which would otherwise be formed in it. For when the liquid reaches the top of the tube, its upper surface, though previously concave, becomes convex, and, as the downward pressure becomes greater than if the surface were plane, the ascending motion ceases.

Insects can often move on the surface of water without sinking. This is a capillary phenomenon caused by the fact, that as their feet are not wetted by the water, a depression is produced which keeps them up in spite of their weight. Similarly a sewing needle gently placed on water, does not sink, because its surface, being covered with an oily layer, does not become wetted. But if washed in alcohol, or in potash, it at once sinks to the bottom.

It is from capillarity the sap rises in plants, that oil ascends in the wicks of lamps, that water rises in wood, sponge, bibulous paper, sugar, sand, and in all bodies which possess pores of a perceptible size.

In the next section, under the heads of endosmose, absorption, and imbibition, we shall become acquainted with some new phenomena which greatly resemble capillarity, and are often confounded with it.

ENDOSMOSE, EFFUSION, ABSORPTION, AND IMBIBITION.

130. **Endosmose and exosmose.**—When two different liquids are separated by a thin porous partition, either inorganic or organic, a current sets in from each liquid to the other; to these currents the names *endosmose* and *exosmose* are respectively given. These terms, which signify *impulse from within* and *impulse from without*, were first introduced by M. Dutrochet, who first drew attention to these phenomena. They may be well illustrated by means of the *endosmometer*. This consists of a long tube, at the end of which a membranous bag is firmly bound (fig. 91). The bag is then filled with a strong syrup, or some other solution denser than water, such as milk or albumen, and is immersed in water. The liquid is found gradually to rise in the tube, to a height which may attain several inches: at the same time, the level of the liquid in which the endosmometer is immersed becomes lower. It follows, therefore, that some of the external liquid has passed through the membrane and has mixed with the internal liquid. The external liquid moreover is found to contain some of the internal liquid. Hence two currents have been produced in opposite directions. The flow of the liquid towards that which increases in volume is *endosmose*, and the current in the opposite direction is *exosmose*. If water is placed in the bag, and immersed in syrup, endosmose is produced from the water towards the syrup, and the liquid in the interior diminishes in volume while the level of the exterior is raised.

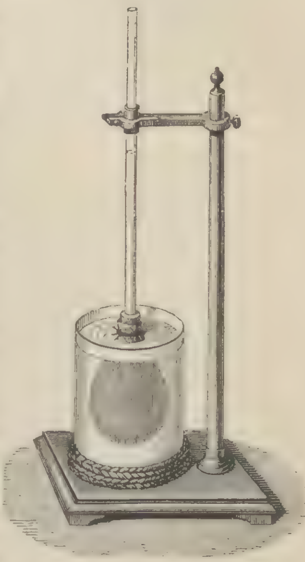


Fig. 91.

The height of the ascent in the endosmometer varies with different liquids. Of all vegetable substances, sugar is that which, for the same density, has the greatest power of endosmose, while albumen has the highest power of all animal substances. In general, it may be said that endosmose takes place towards the denser liquid. Alcohol and ether form an exception to this: they behave like liquids which are denser than water. With acids, according as they are more or less dilute, the endosmose is from the water towards the acid, or from the acid towards water.

According to Dutrochet, it is necessary for the production of endosmose: i. that the liquids be different but capable of mixing, as alcohol and water; there is no endosmose, for instance, with water and oil;

ii. that the liquids be of different densities ; and iii. that the membrane must be permeable to at least one of the substances.

The current through thin inorganic plates is feeble, but continuous, while organic membranes are rapidly decomposed, and endosmose then ceases.

The well-known fact that dilute alcohol kept in a porous vessel becomes concentrated, depends on endosmose. If a mixture of alcohol and water be kept for some time in a bladder, the volume diminishes, but it becomes much more concentrated. The reason, doubtless, is that the bladder permits the endosmose of water rather than that of alcohol.

Dutrochet's method is not adapted for quantitative measurements, for it does not take into account the hydrostatic pressure produced by the column. Jolly has examined the endosmose of various liquids by weighing the bodies diffused. He calls the *endosmotic equivalent* of a substance the number which expresses how many parts by weight of water pass through the bladder in exchange for one part by weight of the substance. The following are some of the endosmotic equivalents which he determined :—

Chloride of sodium . .	4·3	Caustic potass . .	215·0
Sulphate of magnesium .	11·7	Sulphuric acid . .	0·4
„ copper . .	9·5	Alcohol . . .	4·2
Sugar . . .	7·1		

He also found that the endosmotic equivalent increases with the temperature ; and that the quantities of substances which pass in equal times through the bladder are proportional to the strength of the solution.

131. **Diffusion of liquids.**—If oil be poured on water no tendency to intermix is observed, and even if the two liquids be violently agitated together, on allowing them to stand, two separate layers are formed. With alcohol and water the case is different : if alcohol, which is specifically lighter, be poured upon water, the liquids gradually intermix, they diffuse into one another.

The laws of this diffusion, in which no porous diaphragm intervenes, have been completely investigated by Graham. The method, by which his latest experiments were made, was the following :—In a glass vessel containing about 700 cubic centimeters of distilled water, about 100 cubic centimeters of the solution to be examined was carefully added by means of a capillary tube, so as to form a layer on the bottom. After a certain interval of time, successive layers were carefully drawn off by a syphon, and their contents examined.

The general results of these investigations may be thus stated:—

i. When solutions of the same substance, but of different strengths, are taken, the quantities diffused in equal times are proportional to the strengths of the solutions.

ii. In the case of solutions containing equal weights of different substances, the quantities diffused vary with the nature of the substances. Saline substances may be divided into a number of *equidiffusive groups*.

the rates of diffusion of each group being connected with the others by a simple numerical relation.

iii. The quantity diffused varies with the temperature. Thus taking the rate of diffusion of hydrochloric acid at 15° C. as unity; at 49° C. it is 2·18.

iv. If two substances which do not combine be mixed in solution, they may be partially separated by diffusion, the more diffusive one passing out most rapidly. In some cases chemical decomposition even may be effected by diffusion. Thus bisulphate of potassium is decomposed into free sulphuric acid and sulphate of potassium.

v. If liquids be dilute a substance will diffuse into water, containing another substance dissolved as into pure water; but the rate is materially reduced if a portion of the diffusing substance be already present.

The following table gives the approximate times of equal diffusion :—

Hydrochloric acid . .	1·0	Sulphate of magnesium .	7·0
Chloride of sodium . .	2·3	Albumen	49·0
Sugar	7·0	Caramel.	98·0

It will be seen from the above table that the difference between the rates of diffusion is very great. The sulphate of magnesium, one of the least diffusible saline substances, diffuses 7 times as rapidly as albumen and 14 times as rapidly as caramel. These last substances, like hydrated silicic acid, starch, dextrine, gum, etc., constitute a class of substances which are characterised by their incapacity for taking the crystalline form and by the mucilaginous character of their hydrates. Considering gelatine as the type of this class, Graham has proposed to call them *colloids* (κολλή, glue), in contradistinction to the far more easily diffusible *crystalloid* substances.

Graham has proposed a method of separating bodies based on their unequal diffusibility, which he calls *dialysis*. His *dialysis* consists of a ring of gutta percha over which is stretched while wet a sheet of parchment paper, forming thus a vessel about two inches high and ten inches in diameter, the bottom of which is of parchment paper. After pouring in the mixed solution to be dialysed, the whole is floated on a vessel containing a very large quantity of water. In the course of one or two days a more or less complete separation will have been effected. Thus a solution of arsenious acid mixed with various kinds of food readily diffuses out.

The process has received important applications to laboratory and pharmaceutical purposes.

For further information on this subject the student is referred to a very complete article on the diffusion of liquids in the third volume of Watt's Dictionary of Chemistry.

132. **Endosmose of gases.**—The phenomena of endosmose are seen in a high degree in the case of gases. When two different gases are separated by a porous diaphragm, an exchange takes place between them, and ultimately the composition of the gas on both sides of the diaphragm is the same; but the rapidity with which different gases diffuse into each

other under these circumstances varies considerably. The laws regulating this phenomenon have been investigated by Graham. Numerous experiments illustrate it, two of the most interesting of which are the following :—

A glass cylinder closed at one end is filled with carbonic acid gas, its open end tied over with a bladder, and the whole placed under a jar of

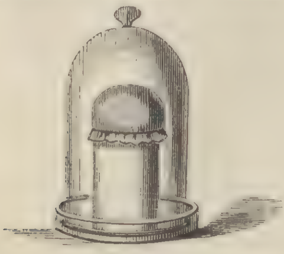


Fig. 92.

Fig. 93.

hydrogen. Diffusion takes place between them through the porous diaphragm, and after the lapse of a certain time hydrogen has passed through the bladder into the cylindrical vessel in much greater quantity than the carbonic acid which has passed out, so that the bladder becomes very much distended outwards (fig. 92). If the cylinder be filled with hydrogen and the bell-jar with carbonic acid, the reverse phenomenon will be produced—the bladder will be distended inwards (fig. 93).

A tube about 12 inches long, closed at one end by a plug of dry plaster of Paris, is filled with dry hydrogen, and its open end then immersed in a mercury bath. Endosmose of the hydrogen towards the air takes place so rapidly that a partial vacuum is produced, and mercury rises in the tube to a height of several inches (fig. 94). If several such tubes are filled with different gases, and allowed to diffuse into the air in a similar manner, in the same time, different quantities of the various gases will diffuse, and Graham found that the law regulating these diffusions is, that *the force of diffusion is inversely as the square roots of the densities of gases.* Thus, if two vessels of equal capacity, containing oxygen and hydrogen, be separated by a porous plug, diffusion takes place ; and after the lapse of some time, for every one part of oxygen which has passed into the hydrogen, four parts of hydrogen have passed into the oxygen. Now the density of hydrogen being 1, that of oxygen is 16, hence the force of diffusion is inversely as the square roots of these numbers. It is four times as great in the one which has $\frac{1}{16}$ the density of the other.

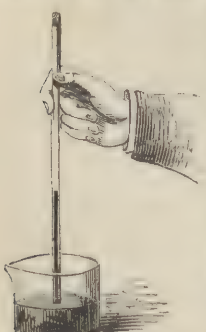


Fig. 94.

133. **Effusion and Transpiration of Gases.**—Effusion is the term applied to the phenomenon of the passage of gases into vacuum, through a minute aperture not much

more or less than 0·013 millimeter in diameter, in a thin plate of metal or of glass. Within the limits of experimental errors, the rates of effusion of different gases coincide with those of their diffusion.

If, however, the gases issue through long, fine capillary tubes into a vacuum, the rate of efflux, or the *velocity of transpiration*, is independent of the rate of diffusion.

i. *For the same gas, the rate of transpiration increases, other things being equal, directly as the pressure*; that is, equal volumes of air of different densities require times inversely proportional to their densities.

ii. *With tubes of equal diameters, the volume transpired in equal times is inversely as the length of the tube.*

iii. *As the temperature rises the transpiration becomes slower.*

iv. *The rate of transpiration is independent of the material of the tube.*

134. **Absorption and imbibition.**—The words absorption and imbibition are used almost promiscuously in physics; they indicate the penetration of a liquid or a gas into a porous body. Absorption is used both for liquids and gases, while imbibition is restricted to liquids.

In physiology an important distinction is made between the two words; absorption means the penetration of a foreign substance into the tissues of a living body, while imbibition refers to penetration into bodies deprived of life, whether organic or not.

135. **Absorption of gases.**—The surfaces of all solid bodies exert an attraction on the molecules of gases with which they are in contact, of such a nature, that they become covered with a more or less thick layer of *condensed gas*. When a porous body, which consequently presents an immensely increased surface in proportion to its size, is placed in a gas over mercury, the great diminution of volume which ensues indicates that considerable quantities of gas are absorbed.

Now, although there is no absorption such as arises from chemical combinations between the solid and gas (as with phosphorus and oxygen), still the quantity of gas absorbed is not entirely dependent on the physical conditions of the solid body; it is influenced in some measure by the chemical nature both of the solid and the gas. Of all bodies boxwood charcoal has the greatest absorptive power. One volume of this substance at the ordinary temperature and pressure absorbs the following quantities of gas :—

Ammonia . . .	90 vol.	Carbonic oxide . . .	9·4 vol.
Hydrochloric acid . .	85 „	Oxygen	9·2 „
Sulphurous „ . .	65 „	Nitrogen	7·5 „
Sulphuretted hydrogen .	55 „	Hydrogen	1·75 „
Carbonic acid . .	35 „		

The absorptive power of pine charcoal is half as much as that of boxwood. The charcoal made from corkwood, which is very porous, is not absorbent; neither is graphite. Platinum, in the finely divided form known as platinum sponge, is said to absorb 250 times its volume of oxygen gas. Many other porous substances, such as meerschaum, gypsum, silk, etc., are also highly absorbent.

136. **Absorption in plants.**—Absorption takes place in all parts of the plant, but more especially in the rootlets and by the leaves. These organs absorb, in the form of water, carbonic acid, and ammonia, the oxygen, hydrogen, carbon, and nitrogen necessary for the growth of the plants.

Liquids, and the salts which they hold in solution, are absorbed by the rootlets, by a double process of capillarity and endosmose. The sap, which is then elaborated by the plant, increasing in density towards the higher part, owes its ascending direction to endosmose. The ascent of the sap is also promoted by the vacuum which the exhalations through the leaves tend to produce. Capillary action can only raise the liquid in the lower cells; it cannot produce a current.

137. **Absorption in animals.**—In the lower animals whose tissues are formed only of cellules, nutrition is accomplished as in plants by absorption and endosmose. The absorption by which some of these animals are nourished is in reality endosmose.

In the higher animals also absorption is met with. Madder administered to an animal penetrates its bones and colours them red. If a liquid is in contact with a cutaneous surface from which the epidermis has been removed, or with a mucous membrane, both which are very vascular, the liquid passes into the vessels by endosmose; this constitutes absorption.

The more liquid a substance, the more readily is it absorbed. At the same time a liquid must moisten a membrane in order to be absorbed. Fatty substances, which do not moisten surfaces, are not absorbed. But M. Bernard has found that when they are made into an emulsion with pancreatic juice, absorption readily takes place. And Dr. Loze has recently observed that cod-liver oil, when made into an emulsion, has a more energetic action, which doubtless arises from its being more completely absorbed.

Like endosmose, absorption is promoted by heat, and also by depletion. After copious perspiration or loss of blood it also increases.

BOOK IV.

ON GASES.

CHAPTER I.

PROPERTIES OF GASES. ATMOSPHERE. BAROMETERS.

138. **Physical properties of gases.**—Gases are bodies whose molecules are in a constant state of repulsion, in virtue of which they possess the most perfect mobility, and are continually tending to occupy a greater space. This property of gases is known by the names *expansibility*, *tension*, or *elastic force*, from which they are often called *elastic fluids*.

Gases and liquids have several properties in common, and some in which they seem to differ are in reality only different degrees of the same property. Thus, in both, the particles are capable of moving; in gases quite freely; in liquids not quite freely, owing to a certain degree of viscosity. Both are compressible, though in very different degrees; if a liquid and a gas both exist under the pressure of one atmosphere, and then the pressure be doubled, the water is compressed by about the $\frac{1}{200000}$ part, while the gas is compressed by one-half. In density there is a great difference: water, which is the type of liquids, is about 800 times as heavy as air, the type of gaseous bodies, while under a pressure of one atmosphere. The property by which gases are distinguished from liquids is their tendency to indefinite expansion.

Matter assumes the solid, liquid, or gaseous form according to the relative strength of the cohesive and repulsive forces exerted between their particles. In liquids these forces balance; in gases repulsion preponderates.

By the aid of pressure and of very low temperatures, the force of cohesion may be so far increased in many gases that they are converted into liquids, and there is every reason for believing that with sufficient pressure and cold they might all be liquefied. On the other hand, heat, which increases the force of repulsion, converts liquids, such as water, alcohol, and ether, into the aëriform state in which they obey all the laws of gases. This aëriform state of liquids is known by the name of *vapour*, while gases are bodies which, under ordinary temperature and pressure, remain in the aëriform state.

In describing the properties of gases we shall, for obvious reasons, have exclusive reference to atmospheric air as their type.

139. **Expansibility of gases.**—This property of gases, their tendency to assume continually a greater volume, is exhibited by means of the following experiment. A bladder closed by a stopcock and about half full of air is placed under the receiver of the air pump (fig. 95) and a vacuum is produced, on which the bladder immediately distends. This arises from the fact that the molecules of air repel each other and press against the sides of the bladder. Under ordinary conditions this internal pressure is counterbalanced by the air in the receiver, which exerts an equal and contrary pressure. But when this pressure is removed by exhausting the receiver, the internal pressure becomes evident. When air is admitted into the receiver the bladder resumes its original form.

Fig. 95.

140. **Compressibility of gases.**—The compressibility of gases is readily shown by the *pneumatic* syringe (fig. 96). This consists of a stout glass tube closed at one end, and provided with a tight-fitting solid piston. When the rod of the piston is pressed, it moves down in the tube, and the air becomes compressed into a smaller volume; but, as soon as the force is removed,

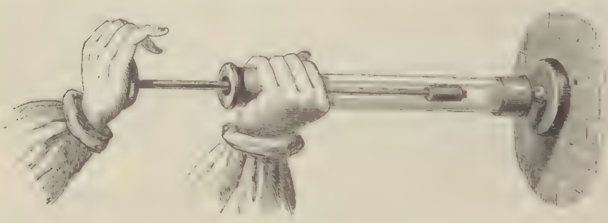


Fig. 96.

the air regains its original volume, and the piston rises to its former position.

141. **Weight of gases.**—From their extreme fluidity and expansibility, gases seem to be uninfluenced by the force of gravity; they nevertheless possess weight, like solids and liquids. To show this, a glass globe of 3 or 4 quarts capacity is taken (fig. 97), the neck of which is provided with a stopcock, which hermetically closes it, and by which it can be screwed to the plate of the air pump. The globe is then exhausted, and its weight determined by means of a delicate balance. Air is now allowed to enter, and the globe again weighed. The weight in the second case will be found to be greater than before, and if the

capacity of the vessel is known, the increase will obviously be the weight of that volume of air.

By a modification of this method, and with the adoption of certain precautions, the weight of air and of other gases has been determined: 100 cubic inches of dry air under the ordinary atmospheric pressure of 30 in. and at the temperature of 16° C., weigh 31 grains; the same volume of carbonic acid gas under the same circumstances weighs 47·25 grains; 100 cubic inches of hydrogen the lightest of all gases, weigh 2·14 grains; and 100 cubic inches of hydriodic acid gas weigh 146 grains.

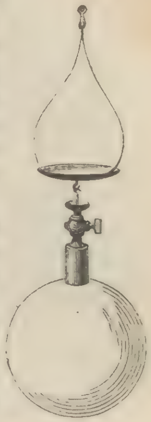


Fig. 97.

The ratio of the density of air at 0° C. and 30 inches pressure to that of water at 0° C. is found to be 0·001296. In other words, the latter is 771 times as heavy as the former.

142. **Pressures exerted by gases.**—Gases exert on their own molecules, and on the sides of vessels which contain them, pressures which may be regarded from two points of view. First, we may neglect the weight of the gas; secondly, we may take account of its weight. If we neglect the weight of any gaseous mass at rest, and only consider its expansive force, it will be seen that the pressures due to this force act with the same intensity on all points, both of the mass itself and of the vessel in which it is contained. For it is a necessary consequence of the elasticity and perfect fluidity of gases, that the repulsive force between the molecules is the same at all points, and acts equally in all directions. This principle of the equality of the pressure of gases in all directions may be shown experimentally by means of an apparatus resembling that by which the same principle is demonstrated for liquids (fig. 51).

If we consider the weight of any gas we shall see that it gives rise to pressures which obey the same laws as those produced by the weight of liquids. Let us imagine a cylinder, with its axis vertical, several miles high, closed at both ends and full of air. Let us consider any small portion of the air enclosed between two horizontal planes. This portion must sustain the weight of all the air above it, and transmit that weight to the air beneath it, and likewise to the curved surface of the cylinder which contains it; and at each point in a direction at right angles to the surface. Thus the pressure increases from the top of the column to the base; at any given layer, it acts equally on equal surfaces, and at right angles to them, whether they are horizontal, vertical, or inclined. The pressure acts on the sides of the vessel, and on any small surface it is equal to the weight of a column of gas, whose base is this surface, and whose height its distance from the summit of the column. The pressure is also independent of the shape and dimensions of the supposed cylinder, provided the height remains the same.

For a small quantity of gas the pressures due to its weight are quite insignificant, and may be neglected; but for large quantities, like the atmosphere, the pressures are considerable, and must be allowed for.

143. **The atmosphere. Its composition.**—The atmosphere is the layer of air which surrounds our globe in every part. It partakes of the rotatory motion of the globe, and would remain fixed relatively to terrestrial objects, but for local circumstances, which produce winds, and are constantly disturbing its equilibrium.

Air was regarded by the ancients as one of the four elements. Modern chemistry, however, has shown that it is a mixture of oxygen and nitrogen gases in the proportion of 20·8 volumes of the former to 79·2 volumes of the latter. By weight it consists of 23 parts of oxygen to 77 parts of nitrogen.

The atmosphere also contains a quantity of aqueous vapour, which varies with the temperature, the season, the locality, and the direction of the winds. It further contains a small quantity of ammoniacal gas, and from 3 to 6 parts in 10,000 of its volume of carbonic acid.

The carbonic acid arises from the respiration of animals, from the processes of combustion, and from the decomposition of organic substances. M. Bousingault has estimated that in Paris the following quantities of carbonic acid are produced every 24 hours :—

By the population and by animals .	11,895,000 cubic feet
By processes of combustion . . .	92,101,000 „
	103,996,000 „

Notwithstanding this enormous continual production of carbonic acid on the surface of the globe, the composition of the atmosphere does not vary; for plants in the process of vegetation decompose the carbonic acid, assimilating the carbon, and restoring to the atmosphere the oxygen which is being continually consumed in the processes of respiration and combustion.

144. **Atmospheric pressure.**—If we neglect the perturbations to which the atmosphere is subject, as being inconsiderable, we may consider it as a fluid sea of a certain depth, surrounding the earth on all sides, and exercising the same pressure as if it were a liquid of very small density. Consequently the pressure on the unit of area is constant at a given level, being equal to the weight of the column of atmosphere above that level whose horizontal section is the unit of area. It will act at right angles to the surface, whatever be its position. It will diminish as we ascend, and increase as we descend from that level. Consequently, at the same height, the atmospheric pressures on unequal plane surfaces will be proportional to the areas of those surfaces, provided they be small in proportion to the height of the atmosphere.

In virtue of the expansive force of the air, it might be supposed that the molecules would expand indefinitely into the planetary spaces. But, in proportion as the air expands, its expansive force decreases, and is further weakened by the low temperature of the upper regions of the atmosphere, so that, at a certain height, an equilibrium is established between the expansive force which separates the molecules, and the action of gravity which draws them towards the centre of the earth. It is therefore concluded that the atmosphere is limited.

From the weight of the atmosphere, and its decrease in density, and

from the observation of certain phenomena of twilight, its height has been estimated at from 30 to 40 miles. Above that height the air is extremely rarefied, and at a height of 60 miles it is assumed that there is a perfect vacuum. From certain observations made in the tropical zone, and particularly at Rio Janeiro, on the twilight arc, M. Liais estimates the height of the atmosphere at between 198 and 212 miles, considerably higher, therefore, than what has hitherto been believed.

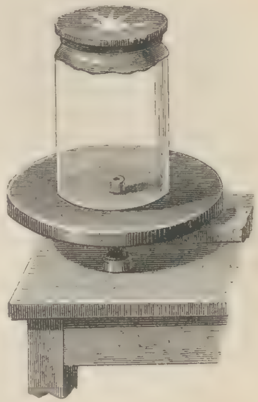


Fig. 98.

As it has been previously stated that 100 cubic inches of air weigh 31 grains, it will readily be conceived that the whole atmosphere exercises a considerable pressure on the surface of the earth. The existence of this pressure is shown by the following experiments.

145. **Crushing force of the atmosphere.** —On one end of a stout glass cylinder, about 5 inches high, and open at both ends, a piece of bladder is tied quite air-tight. The other end, the edge of which is ground and well greased, is pressed on the plate of the air pump (fig. 98). As soon as a vacuum is produced in the

Fig. 99.

Fig. 100.

vessel, by working the air pump, the bladder is depressed by the weight of the atmosphere above it, and finally bursts with a loud report caused by the sudden entrance of the air.

146. **Magdeburg hemispheres.** — The preceding experiment only

serves to illustrate the downward pressure of the atmosphere. By means of the *Magdeburg hemispheres* (figs. 99 and 100), the invention of which is due to Otto von Guericke, burgomaster of Magdeburg, it can be shown that the pressure acts in all directions. This apparatus consists of two hollow brass hemispheres of 4 to 4½ inches diameter, the edges of which are made to fit tightly, and are well greased. One of the hemispheres is provided with a stopcock, by which it can be screwed on the air pump, and on the other there is a handle. As long as the hemispheres contain air they can be separated without any difficulty, for the external pressure of the atmosphere is counterbalanced by the elastic force of the air in the interior. But when the air in the interior is pumped out by means of the air pump, the hemispheres cannot be separated without a powerful effort; and as this is the case in whatever position they are held, it follows that the atmospheric pressure is transmitted in all directions.

DETERMINATION OF THE ATMOSPHERIC PRESSURE. BAROMETERS.

147. **Torricelli's experiment.**—The above experiments demonstrate the existence of the atmospheric pressure, but they give no indications as to its amount. The following experiment, which was first made in 1643 by Torricelli, a pupil of Galileo, gives an exact measure of the weight of the atmosphere.

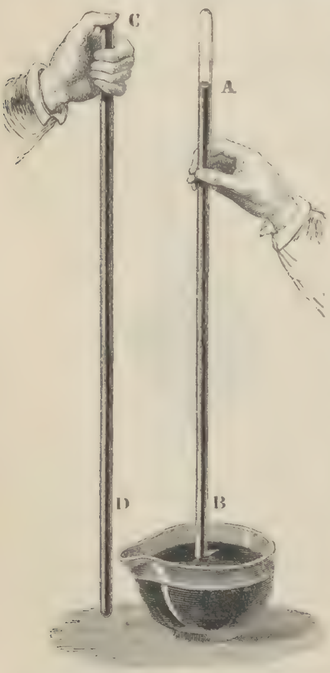


Fig. 101.

A glass tube is taken, about a yard long and a quarter of an inch internal diameter (fig. 101). It is sealed at one end, and is quite filled with mercury. The aperture C being closed by the thumb, the tube is inverted, the open end placed in a small mercury trough, and the thumb removed. The tube being in a vertical position, the column of mercury sinks, and, after oscillating some time, it finally comes to rest at a height A, which at the level of the sea is about 30 inches above the mercury in the trough. The mercury is raised in the tube by the pressure of the atmosphere on the mercury in the trough. There is no contrary pressure on the mercury in the tube, because it is closed. But if the end of the tube be opened the atmosphere will press equally inside and outside the tube, and the mercury will sink to the level of that in the trough. It has been shown in hydrostatics (99) that the heights of two columns of

liquid in communication with each other are inversely as their densities, and hence it follows, that the pressure of the atmosphere is equal to that of a column of mercury, the height of which is 30 inches. If, however, the weight of the atmosphere diminishes, the height of the column which it can sustain must also diminish.

148. **Pascal's experiments.**—Pascal, who wished to prove that the force which sustained the mercury in the tube was really the pressure of the atmosphere, made the following experiments. i. If it were the case, the column of mercury ought to descend in proportion as we ascend in the atmosphere. He accordingly requested one of his relations to repeat Torricelli's experiment on the summit of the Puy de Dôme in Auvergne. This was done, and it was found that the mercurial column was about 3 inches lower, thus proving that it is really the weight of the atmosphere which supports the mercury, since, when this weight diminishes, the height of the column also diminishes. ii. Pascal repeated Torricelli's experiment at Rouen, in 1646, with other liquids. He took a tube closed at one end, nearly 50 feet long, and having filled it with water, placed it vertically in a vessel of water, and found that the water stood in the tube at a height of 34 feet; that is, 13·6 times as high as mercury. But since mercury is 13·6 times as heavy as water, the weight of the column of water was exactly equal to that of the column of mercury in Torricelli's experiment, and it was consequently the same force, the pressure of the atmosphere, which successively supported the two liquids. Pascal's other experiments with oil and with wine gave similar results.

149. **Amount of the atmospheric pressure.**—Let us assume that the tube in the above experiment is a cylinder, the section of which is equal to a square inch, then since the height of the mercurial column in round numbers is 30 inches, the column will contain 30 cubic inches, and as a cubic inch of mercury weighs 3433·5 grains = 0·49 of a pound, the pressure of such a column on a square inch of surface is equal to 14·7 pounds. In round numbers the pressure of the atmosphere is taken at 15 pounds on the square inch. A surface of a foot square contains 144 square inches, and therefore the pressure upon it is equal to 2,160 pounds, or nearly a ton.

A gas or liquid which acts in such a manner that a square inch of surface is exposed to a pressure, 15 pounds, is called a pressure of *one atmosphere.* If, for instance, the elastic force of the steam of a boiler is so great that each square inch of the internal surface is exposed to a pressure of 90 pounds ($= 6 \times 15$), we say it was under a pressure of six atmospheres.

The surface of the body of a man of middle size is about 16 square feet; the pressure, therefore, which a man supports on the surface of his body is 34,560 pounds, or nearly 16 tons. Such an enormous pressure might seem impossible to be borne; but it must be remembered that in all directions there are equal and contrary pressures which counterbalance one another. It might also be supposed that the effect of this force, acting in all directions, would be to press the body together and

crush it. But the solid parts of the skeleton could resist a far greater pressure; and as to the air and liquids contained in the organs and vessels, the air has the same density as the external air, and cannot be further compressed by the atmospheric pressure; and from what has been said about liquids (89) it is clear that they are virtually incompressible. When the external pressure is removed from any part of the body, either by means of a cupping vessel or by the air pump, the pressure from within is seen by the distension of the surface.

150. **Different kinds of barometers.**—The instruments used for measuring the atmospheric pressure are called *barometers.* In ordinary barometers, the pressure is measured by the height of a column of mercury, as in Torricelli's experiment: the barometers which we are about to describe are of this kind. But there are barometers without any liquid, one of which, the aneroid, is remarkable for its simplicity and portability.

151. **Cistern barometer.**—The *cistern barometer* consists of a straight glass tube closed at one end, about 33 inches long, filled with mercury, and dipping into a cistern containing the same metal. In order to render the barometer more portable, and the variations of the level in the cistern less perceptible when the mercury rises or falls in the tube, several different forms have been constructed. Fig. 102 represents one form of the cistern barometer. The apparatus is fixed to a mahogany stand, on the upper part of which there is a scale graduated in millimeters or inches from the level of the mercury in the cistern; a moveable index, *i*, shows on the scale the level of the mercury. A thermometer on the side of the tube indicates the temperature.

There is one fault to which this barometer is liable, in common with all others of the same kind. The zero of the scale does not always correspond to the level of the mercury in the cistern. For as the atmospheric pressure is not always the same, the height of the mercurial column varies: sometimes mercury is forced from the cistern into the tube, and sometimes from the tube into the cistern, so that, in the majority of cases, the graduation of the barometer does not indicate the true height. If the diameter of the cistern is large, relatively to that of the tube, the error from this source is lessened. The *height* of the barometer is the distance between the levels of the mercury in the tube and in the cistern. Hence the barometer should always be perfectly vertical; for, if not, the tube being inclined, the column of mercury is elongated (fig. 103), and the number read off on the scale is too great. As the pressure which the mercury exerts by its weight at the base of the tube is independent of the form of the tube and of its diameter (99), provided it is not capillary, the height of the barometer is independent of the diameter of the tube and of its shape, but is inversely as the density of the liquid. With mercury the mean height at the level of the sea is 29·92, or in round numbers 30, inches; in a water barometer it would be about 33·7 feet.

152. **Fortin's barometer.**—*Fortin's barometer* differs from that just described, in the shape of the cistern. The base of the cistern is made of

leather, and can be raised or lowered by means of a screw; this has the advantage, that a constant level can be obtained, and also that the instrument is made more portable. For, in travelling, it is only necessary to raise the leather until the mercury, which rises with it, quite fills the cistern; the barometer may then be inclined, and even inverted without any fear that a bubble of air may enter, or that the shock of the mercury may crack the tube.

Fig. 102.

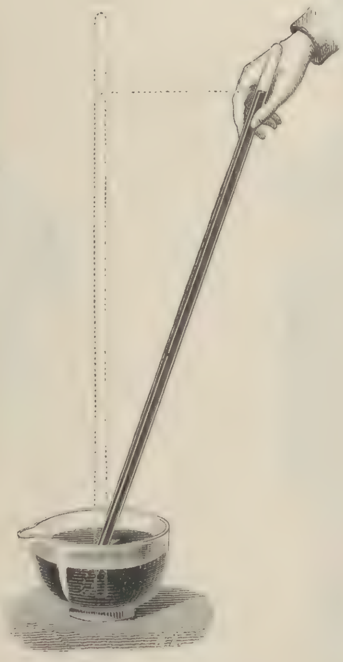


Fig. 103.

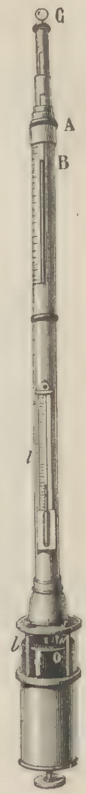


Fig. 104.

Fig. 104 represents the arrangement of the barometer, the tube of which is placed in a brass case. At the top of this case, there are two longitudinal apertures, on opposite sides, so that the level of the mercury, B, is seen. The scale on the case is graduated in millimeters. An index A moved by the hand, gives, by means of a vernier, the height of the mer-

cury to $\frac{1}{10}$ of a millimeter. At the bottom of the case there is the cistern *b*, containing mercury, O.

Fig. 105 shows the details of the cistern on a larger scale. It consists of a glass cylinder *b*, through which the mercury can be seen ; this is closed at the top by a box-wood disc fitted on the under-surface of the brass cover M. Through this passes the barometer tube E, which is drawn out at the end, and dips in the mercury; the cistern and the tube are connected by a piece of buckskin *ce*, which is firmly tied at *c* to a contraction in the tube, and at *e* to a brass tubulure in the cover of the cistern. This mode of closing prevents the mercury from escaping when

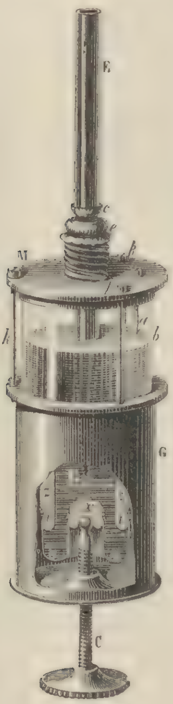


Fig. 105.

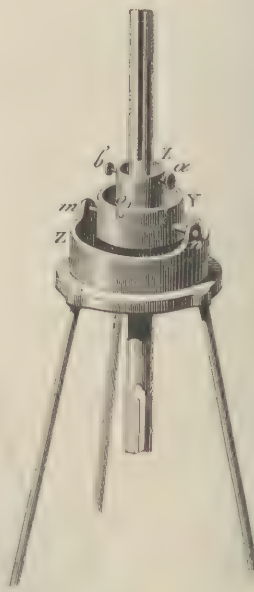


Fig. 106.

the barometer is inverted, while the pores of the leather transmit the atmospheric pressure. The bottom of the cylinder *b* is cemented on a box-wood cylinder *zz*, on a contraction in which, *ii*, is firmly tied the buckskin *mn*, which forms the base of the cistern. On this skin is fastened a wooden button *x*, which rests against the end of a screw C. According as this is turned in one direction or the other, the skin *mn* is raised or lowered ; and with it the mercury. In using this barometer the mercury is first

made exactly level with the point *a*, which is affected by turning the screw C either in one direction or the other. The graduation of the scale is counted from this point *a*, and thus the distance of the top B of the column of mercury from *a* gives the height of the barometer. The bottom of the cistern is surrounded by a brass case, which is fastened to the cover M by screws, *k*, *k*, *k*. We have already seen (151) the importance of having the barometer quite vertical, which is effected by the following means, known as *Cardan's suspension.*

The metal case containing the barometer is fixed in a copper sheath X by two screws *a* and *b* (fig. 106). This is provided with two axles (only one of which, *o*, is seen in the figure), which turn freely in two holes in a ring Y. In a direction at right angles to that of the axles, *oo*, the ring has also two similar axles, *m* and *n*, resting on a support Z. By means of this double suspension, the barometer can oscillate freely about the axis, *mn* and *oo*, in two directions at right angles to each other. But as care is taken that the point at which these cross corresponds to the tube itself, the centre of gravity of the system, which must always be lower than the axis of suspension, is below the point of intersection, and the barometer is then perfectly vertical.

153. **Gay-Lussac's syphon barometer.**—The syphon barometer is a bent glass tube, one of the branches of which is much longer than the other. The longer branch, which is closed at the top, is filled with mercury as in the cistern barometer, while the shorter branch, which is open, serves as a cistern. The difference between the two levels is the height of the barometer.

Fig. 107 represents the syphon barometer as modified by Gay-Lussac. In order to render it more available for travelling by preventing the entrance of air, he joined the two branches by a capillary tube; when the instrument is inverted, the tube always remains full in virtue of its capillarity, and air cannot penetrate into the longer branch. A sudden shock, however, might separate the mercury and admit some air. To avoid this, M. Bunten has introduced an ingenious modification into the apparatus. The longer branch is drawn out to a fine point, and is joined to a tube K, of the form represented in fig. 108. By this arrangement, if air passes through the capillary tube it cannot penetrate the drawn out extremity of the longer branch, but lodges in the upper part of the enlargement K. In this position it does not affect the observations, since the vacuum is always at the upper part of the tube; it is moreover easily removed.

Fig. 108.

Fig. 107.

In Gay-Lussac's barometer the shorter branch is closed, but there is

a lateral capillary aperture a, through which the atmospheric pressure is transmitted.

The barometric height is determined by means of two scales, which have a common zero at O, towards the middle of the longer branch, and are graduated in contrary directions, the one from O to E, and the other from O to B, either on the tube itself, or on brass rules fixed parallel to the tube. Two sliding verniers, m and n, indicate $\frac{1}{10}$ of a millimeter. The total height of the barometer, AB, is the sum of the distances from O to A and from O to B.

154. **Precautions in reference to barometers.**—In constructing barometers, mercury is chosen in preference to any other liquid. For being the densest of all liquids it stands at the least height. When the mercurial barometer stands at 30 inches, the water barometer would stand at about 34 feet. It also deserves preference because it does not moisten the glass. It is necessary that the mercury be pure and free from oxide; otherwise it adheres to the glass and tarnishes it. Moreover if it is impure its density is changed, and the height of the barometer is too great or too small. Mercury is purified, before being used for barometers, by treatment with dilute nitric acid, and by distillation.

The space at the top of the tube (figs. 101 and 102), which is called the *Torricellian vacuum*, must be quite free from air and from aqueous vapour, for otherwise either would depress the mercurial column by its elastic force. To obtain this result, a small quantity of pure mercury is placed in the tube and boiled for some time. It is then allowed to cool, and a further quantity, previously warmed, added, which is boiled, and so on, until the tube is quite full; in this manner the moisture and the air which adhere to the sides of the tube pass off with the mercurial vapour.

A barometer is free from air and moisture if, when it is inclined, the mercury strikes with a sharp metallic sound against the top of the tube. If there is air or moisture in it, the sound is deadened.

155. **Correction for capillarity.**—In cistern barometers there is always a certain depression of mercurial column due to capillarity, unless the internal diameter of the tube exceeds 0·8 inch. To make the correction due to this depression, it is not enough to know the diameter of the tube, we must also know the height of the meniscus od (fig. 109), which varies according as the meniscus has been formed during an ascending or descending motion of the mercury in the tube. Consequently the height of the meniscus must be determined by bringing the pointer to the level ab, and then to the level d, when the difference of the readings will give the height od required. These two terms, namely, the internal diameter of the tube and the height of the meniscus, being known, the resulting correction can be taken out of the following table, which follows the arrangement frequently adopted for a multiplication table :—

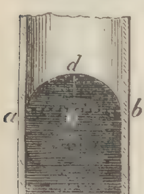


Fig. 109.

Internal Diameter in inches	Height of Sagitta of Meniscus in inches						
	0·010	0·015	0·020	0·025	0·030	0·035	0·040
0·157	0·0293	0·0431	0·0555	0·0677	0·0780	0·0870	0·0948
0·236	0·0119	0·0176	0·0231	0·0294	0·0342	0·0398	0·0432
0·315	0·0060	0·0088	0·0118	0·0144	0·0175	0·0196	0·0221
0·394	0·0039	0·0048	0·0063	0·0078	0·0095	0·0110	0·0125
0·472	0·0020	0·0029	0·0036	0·0045	0·0053	0·0063	0·0073
0·550	0·0010	0·0017	0·0024	0·0029	0·0034	0·0039	0·0044

In Gay-Lussac's barometer the two tubes are made of the same diameter, so that the error caused by the depression in the one tube very nearly corrects that caused by the depression in the other. As, however, the meniscus in the one tube is formed by a column of mercury with an ascending motion, while that in the other by a column with a descending motion, their heights will not be the same, and the reciprocal correction will not be quite exact.

156. **Correction for temperature.**—In all observations with barometers, whatever be their construction, a correction must be made for temperature. Mercury contracts and expands with different temperatures; hence its density changes, and consequently the barometric height, for this height is in the inverse ratio of the density of the mercury; so that for different atmospheric pressures the mercurial column might have the same height. Accordingly, in each observation, the height observed must be reduced to a determinate temperature; the choice of this is quite arbitrary, but that of melting ice is always adopted. It will be seen, in the Book on Heat, how this correction is made.

By the aid of tables which have been prepared for this purpose, the height of the barometer is readily reduced to zero Centigrade.

157. **Variations in the height of the barometer.**—When the barometer is observed for several days, its height is found to vary in the same place, not only from one day to another, but also during the same day.

The extent of these variations, that is, the difference between the greatest and the least height, is different in different places. It increases from the equator towards the poles. Except under extraordinary circumstances, the greatest variations do not exceed 6 millimeters under the equator, 30 under the tropic of Cancer, 40 in France, and 60 at 25 degrees from the pole. The greatest variations are observed in winter.

The *mean daily height* is the height obtained by dividing the sum of 24 successive hourly observations by 24. In our latitudes, the barometric height at noon corresponds to the mean daily height.

The *mean monthly height* is obtained by adding together the mean daily heights for a month, and dividing by 30.

The *mean yearly height* is similarly obtained.

Under the equator, the mean annual height at the level of the sea is

$0^m{\cdot}758$, or 29·84 inches. It increases from the equator, and between the latitudes 30° and 40° it attains a maximum of $0^m{\cdot}763$, or 30·04 inches. In lower latitudes it decreases, and in Paris it does not exceed $0^m{\cdot}7568$.

The general mean at the level of the sea is $0^m{\cdot}761$, or 29·96 inches.

The mean monthly height is greater in winter than in summer, in consequence of the cooler atmosphere.

Two kinds of variations are observed in the barometer: 1st, the *accidental variations*, which present no regularity; they depend on the seasons, the direction of the winds, and the geographical position, and are common in our climates: 2nd, the *daily variations*, which are produced periodically at certain hours of the day.

At the equator, and between the tropics, no accidental variations are observed; but the daily variations take place with such regularity that a barometer may serve to a certain extent as a clock. The barometer sinks from midday till towards four o'clock; it then rises, and reaches its maximum at about ten o'clock in the evening. It then again sinks, and reaches a second minimum towards four o'clock in the morning, and a second maximum at ten o'clock.

In the temperate zones there are also daily variations, but they are detected with difficulty, since they occur in conjunction with accidental variations.

The hours of the maxima and minima appear to be the same in all climates, whatever be the latitude; they merely vary a little with the seasons.

158. **Causes of barometric variations.**—It is observed that the course of the barometer is generally in the opposite direction to that of the thermometer; that is, that when the temperature rises the barometer falls, and *vice versa*; which indicates that the barometric variations at any given place are produced by the expansion or contraction of the air, and therefore by its change in density. If the temperature were the same throughout the whole extent of the atmosphere, no currents would be produced, and, at the same height, the atmospheric pressure would be everywhere the same. But when any portion of the atmosphere becomes warmer than the neighbouring parts, its specific gravity is diminished, and it rises and passes away through the upper regions of the atmosphere, whence it follows that the pressure is diminished, and the barometer falls. If any portion of the atmosphere retains its temperature, while the neighbouring parts become cooler, the same effect is produced; for in this case, too, the density of the first-mentioned portion is less than that of the others. Hence, also, it usually happens that an extraordinary fall of the barometer at one place is counterbalanced by an extraordinary rise at another place. The daily variations appear to result from the expansions and contractions which are periodically produced in the atmosphere by the heat of the sun during the rotation of the earth.

159. **Relation of barometric variations to the state of the weather.**—It has been observed that, in our climate, the barometer in fine weather is generally above 30 inches, and is below this point when there is rain, snow, wind, or storm, and also, that for any given number of days at

which the barometer stands at 30 inches, there are as many fine as rainy days. From this coincidence between the height of the barometer and the state of the weather, the following indications have been marked on the barometer, counting by thirds of an inch above and below 30 inches :

Height	State of the weather
31 inches	Very dry.
$30\frac{2}{3}$ "	Settled weather.
$30\frac{1}{3}$ "	Fine weather.
30 "	Variable.
$29\frac{2}{3}$ "	Rain or wind.
$29\frac{1}{3}$ "	Much rain.
29 "	Tempest.

In using the barometer as an indicator of the state of the weather, we must not forget that it really only serves to measure the weight of the atmosphere, and that it only rises or falls as this weight increases or diminishes ; and although a change of weather frequently coincides with a change in the pressure, they are not necessarily connected. This coincidence arises from meteorological conditions peculiar to our climate, and does not always occur. That a fall in the barometer usually precedes rain in our latitudes, is caused by the position of Europe. The south-west winds, which are hot and consequently light, make the barometer sink; but at the same time, as they become charged with aqueous vapour in crossing the ocean, they bring us rain. The winds of the north and north-east, on the contrary, being colder and denser, make the barometer rise ; and as they only reach us after having passed over vast continents they are generally dry.

When the barometer rises or sinks slowly, that is, for two or three days, towards fine weather or towards rain, it has been found from a great number of observations that the indications are then extremely probable. Sudden variations in either direction indicate bad weather or wind.

Fig. 110.

Fig. 111.

160. **Wheel barometer.**—The *wheel barometer*, which was invented by Hooke, is a syphon barometer, and is especially intended to indicate good and bad weather (fig. 110). In the shorter leg of the syphon there is a float, which rises and falls with the

mercury (fig. 111). A string attached to this float passes round a pulley, O, and at the other end there is a weight, P, somewhat lighter than the float. A needle fixed to the pulley moves round a graduated circle, on which is marked, *variable*, *rain*, *fine weather*, etc. When the pressure varies the float sinks or rises, and moves the needle round to the corresponding points on the scale.

The barometers ordinarily met with in houses, and which are called *weather glasses*, are of this kind. They are, however, of little use, for two reasons. The first is, that they are neither very delicate nor precise in their indications. The second, which applies equally to all barometers, is, that those commonly in use in this country are made in London, and the indications, if they are of any value, are only so for a place of the same level and of the same climatic conditions as London. Thus a barometer standing at a certain height in London would indicate a certain state of weather, but if removed to Shooter's Hill it would stand half an inch lower, and would indicate a different state of weather. As the pressure differs with the level and with geographical conditions, it is necessary to take these into account if exact data are wanted.

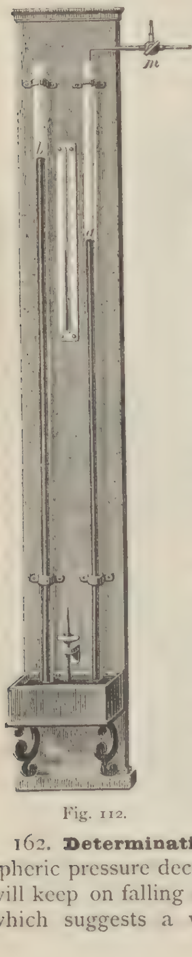


Fig. 112.

161. **Fixed barometer.**—For accurate observations Regnault uses a barometer the height of which he measures by means of a cathetometer (80). The cistern (fig. 112) is of cast iron; against the frame on which it is supported a screw is fitted, which is pointed at both ends, and the length of which has been determined, once for all, by the cathetometer. To measure the barometric height the screw is turned until its point grazes the surface of the mercury in the bath, which is the case when the point and its image are in contact. The distance then from the top of the point to the level of the mercury in the tube *b* is measured by the cathetometer, and this together with the length of the screw gives the barometric height with great accuracy. This barometer has moreover the advantage that, as a tube an inch in diameter may be used, the influence of capillarity becomes inappreciable. Its construction moreover is very simple, and the position of the scale leads to no kind of error since this is transferred to the cathetometer. Unfortunately the latter instrument requires great accuracy in its construction, and is very expensive.

162. **Determination of heights by the barometer.**—Since the atmospheric pressure decreases as we ascend, it is obvious that the barometer will keep on falling as it is taken to a greater and greater height—a fact which suggests a very useful method of determining the difference

between the elevations of two stations, such as the base and summit of a mountain. The method may be explained as follows.

It will be seen in the next chapter that if the temperature of an enclosed portion of air continues constant, its volume will vary inversely as the pressure per square inch. That is to say, if we double the pressure we shall halve the volume. This fact is commonly called Boyle's law. But if we halve the volume we manifestly double the quantity of air, in each cubic inch, or double the density of the air, and so on in any proportion. Consequently, the law is equivalent to this:—That for a constant temperature the density of air is proportional to the pressure per square inch which it sustains.

Fig. 113.

Now suppose A and B (fig. 113) to represent two stations, and that it is required to determine the vertical height of B above A; it being borne in mind that A and B are not necessarily in the same vertical line. Take P any point in AB, and Q a point at a small distance above P. Suppose the pressure per square inch of the atmosphere at P to be denoted by p, and at Q let it be diminished by a quantity denoted by dp. It is plain that this diminution equals the weight of the column of air between P and Q, whose section is one square inch. But, since the density of the air is directly proportional to p, the weight of a cubic inch of air will equal kgp, where k denotes a certain quantity to be determined hereafter, and g the accelerating force of gravity (71). Hence, if we denote PQ in inches by dx, the pressure will be diminished by $kpg.dx$, and we may represent this fact algebraically by the equation

$$kpg.dx = dp.$$

By a well-known algebraical process this leads to the conclusion that

$$kg\mathrm{X} = \log \frac{\mathrm{P}}{\mathrm{P}_1}$$

where X denotes the height of AB, and P and P_1 the atmospheric pressures at A and B respectively, the logarithms being of the kind called 'Napierian logarithms.' Now, if H and H_1 are the heights of the barometer at A and B respectively, the temperature of the mercury being the same at both stations, their ratio equals that of P to P_1, and therefore

$$\mathrm{X} = \frac{1}{kg} \cdot \log \frac{\mathrm{H}}{\mathrm{H}_1}$$

It remains to determine k and g.

(1) Since the force of gravity is different for places in different latitudes, g will depend upon the latitude (74). It is found that if g is the accelerating force of gravity in latitude ϕ, and f that force in latitude 45°, then

$$g = \frac{f}{1 + 0{\cdot}00256 \cos 2\phi}$$

where f has a definite numerical value.

(2) From what has been stated above it will be seen, that if ρ is the

density of air at a temperature of $t°$ C., under Q the pressure exerted by 29·92 inches of mercury, we shall have

$$kQ = \rho$$

But it appears that if ρ_0 is the density of air under the same pressure Q at 0° C., we shall have

$$\rho = \frac{\rho_0}{1 + \alpha t}$$

Where α has a definite numerical value. Therefore

$$kQ = \frac{\rho_0}{1 + \alpha t}$$

Now if σ is the density of mercury, and if the latitude is 45°, we shall have

$$Q = 29{\cdot}92 \ . \ \sigma f;$$

and therefore

$$kf = \frac{\rho_0}{\sigma} \cdot \frac{1}{29{\cdot}92(1 + \alpha t)}$$

Now $\rho_0 \div \sigma$ is the ratio which the density of dry air at a temperature 0° C., in latitude 45°, under a pressure of 29·92 inches of mercury, bears to the density of mercury at 0° C., and therefore $\rho_0 \div \sigma$ is a determinate number. Substituting

$$X = 29{\cdot}92 \text{ in. } . \ \frac{\sigma}{\rho_0} (1 + 0{\cdot}00256 \ \cos 2\phi \ (1 + \alpha t) \log \frac{H}{H_1}$$

The value of α is 0·003665, which is nearly equal to $\frac{4}{1000}$. If we substitute the proper values for $\sigma \div \rho_0$, and change the logarithms into common logarithms, and instead of t use the mean of T and T_1, the temperatures at the upper and lower stations, it will be found that

$$X \text{ (in feet} = 60346 \ (1 + 0{\cdot}00256 \cos 2\phi) \left(1 + \frac{2(T + T_1)}{1000}\right) \log \frac{H}{H_1}$$

which is La Place's barometric formula. In using it, it must be remembered that T and T_1 are temperatures on the Centigrade thermometer, and that H and H_1 are the heights of the barometer reduced to 0° C. Thus if h is the measured height of the barometer at the lower station we have

$$H = h\left(1 - \frac{t}{6500}\right)$$

If the height to be measured is not great, one observer is enough. For greater heights the ascent takes some time, and in the interval the pressure may vary. Consequently in this case there must be two observers, one at each station, who make simultaneous observations.

Let us take the following example of the above formula :—Suppose that in latitude 65° N. at the lower of the two stations the height of the barometer were 30·025 inches, and the temperature of air and mercury 17°·32 C., while at the upper the height of the barometer was 28·230 inches, and the temperature of air and mercury was 10°·55 C. Determine the height of the upper station above the lower.

(1) Find H and H_1: viz.

$$H = 30{\cdot}025\left(1 - \frac{17{\cdot}32}{6500}\right) = 29{\cdot}945$$

$$H_1 = 28{\cdot}230\left(1 - \frac{10{\cdot}55}{6500}\right) = 28{\cdot}185$$

$$\text{Hence } \log\frac{H}{H_1} = 1{\cdot}4763243 - 1{\cdot}4500155 = 0{\cdot}02562688$$

(2) Find $1 + \frac{2(T+T_1)}{1000}$ viz. $1{\cdot}05574$

(3) Find $1 + 0{\cdot}00256 \cos 2\phi$

Since $0{\cdot}00256 \cos 130° = -0{\cdot}00256 \cos 50°$

$$= -0{\cdot}001824$$

therefore $1 + 0{\cdot}00256 \cos 2\phi = -0{\cdot}998355$

Hence the required height in feet equals

$$60346 \times 0{\cdot}998355 \times 1{\cdot}05574 \times 0{\cdot}02562688 = 1671$$

It may be easily proved that if H and H_1 do not greatly differ, the Napierian logarithm of $\frac{H}{H_1}$ equals $2\,\frac{H-H_1}{H+H_1}$. If for instance H equals 30 inches, and H_1 equals 29 inches, the resulting error would not exceed the $\frac{1}{5000}$ part of the whole. Accordingly for heights not exceeding 2000 ft. we may without much error use the formula,

$$X \text{ (in feet)} = 52500\left(1 + \frac{2(T+T_1)}{1000}\right) \times \frac{H-H_1}{H+H_1}$$

CHAPTER II.

MEASUREMENT OF THE ELASTIC FORCE OF GASES.

163. **Boyle's law.**—The law of the compressibility of gases was discovered by Boyle and Mariotte independently. In consequence it is in England commonly called 'Boyle's law,' and, on the Continent, 'Mariotte's law.' It is as follows :

'*The temperature remaining the same, the volume of a given quantity of gas is inversely as the pressure which it bears.*'

This law is verified by means of an apparatus called *Mariotte's tube* (fig. 114). It consists of a long glass tube fixed to a vertical support; it is open at the upper part, and the other end, which is bent into a short vertical leg, is closed. On the shorter leg there is a scale, which indicates equal capacities; the scale against the long leg gives the heights. The zero of both scales is in the same horizontal line.

A small quantity of mercury is poured into the tube, so that its level in both branches is at zero, which is effected without much difficulty after a few trials (fig. 114). The air in the short leg is thus under the ordinary atmospheric pressure which is exerted through the open tube. Mercury is then poured into the longer tube until the volume of the air in the smaller tube is reduced to one-half; that is, until it is reduced from 10 to 5, as shown in fig. 115. If the height of the mercurial column, CA, be measured, it will be found exactly equal to the height of the barometer at

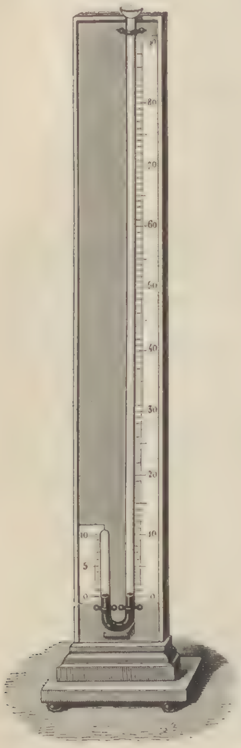


Fig. 114.

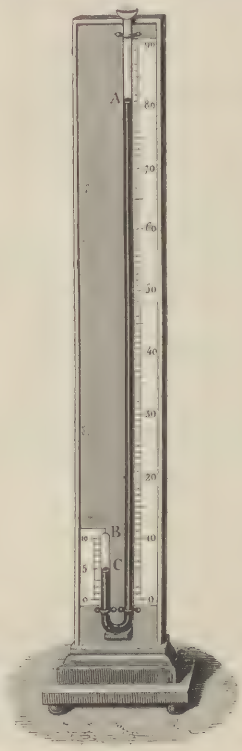


Fig. 115.

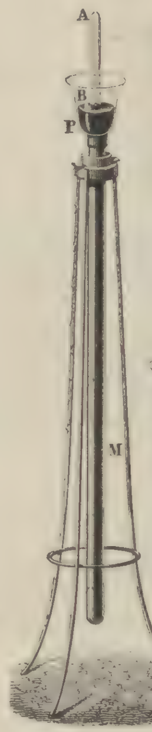


Fig. 116.

Fig. 117

the time of the experiment. The pressure of the column CA is therefore equal to an atmosphere which, with the atmospheric pressure acting on the surface of the column at C, makes two atmospheres. Accordingly, by doubling the pressure, the volume of the gas has been diminished to one-half.

If mercury be poured into the longer branch until the volume of the air is reduced to one-third its original volume, it will be found that the distance between the level of the two tubes is equal to two barometric columns. The pressure is now three atmospheres, while the volume is

reduced to one-third. Dulong and Petit have verified the law for air up to 27 atmospheres, by means of an apparatus analogous to that which has been described.

The law also holds good in the case of pressures of less than one atmosphere. To establish this, mercury is poured into a graduated tube until it is about two-thirds full, the rest being air. It is then inverted in a deep trough containing mercury (fig. 116), and lowered until the levels of the mercury inside and outside the tube are the same, and the volume noted. The tube is then raised, as represented in the figure, until the volume of air AC is double that of AB (fig. 117). The height of the mercury in the tube, above the mercury in the trough CD, is then found to be exactly half the height of the barometric column. The air, whose volume is now doubled, is now only under the pressure of half an atmosphere; for it is the elastic force of this air which, added to the weight of the column CD, is equivalent to the atmospheric pressure. Hence the volume is inversely as the pressure.

In the experiment with Mariotte's tube, as the quantity of air remains the same, its density must obviously increase as its volume diminishes, and *vice versa.* The law may thus be enunciated: '*For the same temperature the density of a gas is proportional to its pressure.*' Hence, as water is 770 times as heavy as air, under a pressure of 770 atmospheres, air would be as dense as water.

164. **Boyle's law is only approximately true.**—Until within the last few years Boyle's law was supposed to be absolutely true for all gases at all pressures, but Despretz, who examined the compressibility of gases, obtained results incompatible with the law. He took two graduated glass tubes of the same length, and filled one with air and the other with the gas to be examined. These tubes were placed in the same mercury trough, and the whole apparatus immersed in a strong glass cylinder filled with water. By means of a piston moved by a screw which worked in a cap at the top of a cylinder, the liquid could be subjected to an increasing pressure, and it could be seen whether the compression of the two gases was the same or not. The apparatus resembled that used for examining the compressibility of liquids (fig. 49). In this manner Despretz found that carbonic acid, sulphuretted hydrogen, ammonia, and cyanogen, are more compressible than air: hydrogen, which has the same compressibility as air up to 15 atmospheres, is then less compressible. From these experiments it was concluded that the law of Boyle was not general.

In some experiments on the elastic force of vapours, Dulong and Arago had occasion to test the accuracy of Boyle's law. The method adopted was exactly that of Mariotte, but the apparatus had gigantic dimensions.

The gas to be compressed was contained in a strong glass tube, GF (fig. 118), about six feet long and closed at the top, G. The pressure was produced by a column of mercury, which could be increased to a height of 65 feet, contained in a long vertical tube, KL, formed of a number of tubes firmly joined by good screws, so as to be perfectly tight.

The tubes KL and GF were hermetically fixed in a horizontal iron pipe, DE, which formed part of a mercurial reservoir, A. On the top of this reservoir there was a force pump, BC, by which mercury could be forced into the apparatus.

At the commencement of the experiment, the volume of the air in the manometer (168) was observed, and the initial pressure determined, by adding to the pressure of the atmosphere the height of the mercury in K

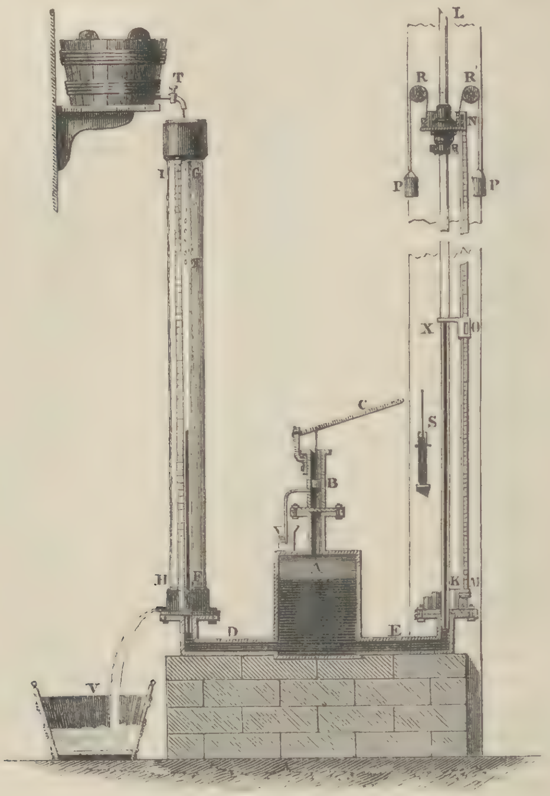


Fig. 118.

above its level in H. If the level of the mercury in the manometer had been above the level in KL, it would have been necessary to subtract the difference.

By means of the pump, water was injected into A. The mercury being then pressed by the water, rose in the tube GF, where it compressed the air, and in the tube KL, where it rose freely. It was only then necessary to measure the volume of the air in GF; the height of the

mercury in KL above the level in GF, together with the pressure of the atmosphere, was the total pressure to which the gas was exposed. These were all the elements necessary for comparing different volumes and the corresponding temperatures. The tube GF was kept cold during the experiment by a stream of cold water.

The long tube was attached to a long mast by means of staples. The individual tubes were supported at the junction by cords, which passed round pulleys R and R′, and were kept stretched by small buckets, P, containing shot. In this manner, each of the thirteen tubes having been separately counterpoised, the whole column was perfectly free, notwithstanding its weight.

Dulong and Arago investigated the pressure up to 27 atmospheres, and observed that the volume of air always diminished a little more than is required by Boyle's law. But, as these differences were very small, they attributed them to errors of observation, and concluded that the law was perfectly exact, at any rate up to 27 atmospheres.

M. Regnault investigated the same subject with an apparatus resembling that of Dulong and Arago, but in which all the sources of error were taken into account, and the observations made with remarkable precision. He experimented with air, nitrogen, carbonic acid, and hydrogen. He found that air does not exactly follow Boyle's law, but experiences a greater compressibility, which increases with the pressure; so that the difference between the calculated and the observed diminution of volume is greater in proportion as the pressure increases.

M. Regnault found that nitrogen was like air, but is less compressible. Carbonic acid exhibits considerable deviation from Boyle's law even under small pressures. Hydrogen also deviates from the law, but its compressibility diminishes with increased pressure.

Carbonic acid deviates less from the law in proportion as the temperature is higher. This is also the case with other gases. And experiment shows that the deviation from the law is greater, in proportion as the gas is nearer its liquefying point; and, on the contrary, the farther a gas is from this point, the more closely does it follow the law. For gases which have not been liquefied, the deviations from the law are inconsiderable, and may be quite neglected in ordinary physical and chemical experiments, where the pressures are not great.

165. **Applications of Boyle's law.**—Observations on the volumes of gases are only comparable when made at the same pressure. Usually, therefore, in gas analyses, all measurements are reduced to the standard pressure of 760 millimeters, or 29·92 inches. This is easily done by Boyle's law, for, since the volumes are inversely as the pressures, $V : V' = P' : P$. Knowing the volume V at the pressure P we can easily calculate its volume V′ at the given pressure P′, for

$$V'P' = VP$$

that is,

$$V' = \frac{VP}{P'}$$

Suppose a volume of gas to measure 340 cubic inches under a pressure of 535 mm., what will be its volume at the standard pressure, 760 mm.?

We have $$V = \frac{340 \times 535}{760} = 238 \text{ cubic inches.}$$

In like manner let it be asked, if D′ is the density of a gas when the barometer stands at H′ mm., what will be its density D at the same temperature when the barometer stands at H mm? Let M be the mass of the gas, V′ its volume in the first case, V its volume in the second. Therefore,

$$DV = M = D'V'$$

or,

$$\frac{D}{D'} = \frac{V'}{V} = \frac{P}{P'} = \frac{H}{H'}$$

Thus, if H′ denote 760 mm., we have

$$\text{Density at } H = (\text{Density at standard pressure}) \frac{H}{760}$$

166. **Manometers.**—Manometers are instruments for measuring the tension of gases or vapours. In all manometers the unit chosen is the pressure of one atmosphere or 30 inches of mercury at the standard temperature, which, as we have seen, is nearly 15lbs. to the square inch.

167. **Open-air manometer.**—The open-air manometer consists of a bent glass tube BD (fig. 119), fastened to the bottom of a reservoir AC, of the same material, containing mercury, which is connected with the closed recipient containing the gas or vapour the pressure of which is to be measured. The whole is fixed on a long plank kept in a vertical position.

In graduating this manometer C is left open, and the number 1 marked at the level of the mercury, for this represents one atmosphere. From this point at each 30 inches the numbers 2, 3, 4, 5, 6 are marked, indicating so many atmospheres, since a column of mercury 30 inches represents a pressure of one atmosphere. The intervals from 1 to 2, and from 2 to 3, &c., are divided into tenths. C being then placed in connection with a boiler, for example, the mercury rises in the tube BD to a height which measures the tension of the vapour. In the figure the manometer marks 2 atmospheres, which represents a height of 30 inches, plus the atmospheric pressure exerted at the top of the column through the aperture D.

This manometer is only used when the pressures do not exceed 5 to 6 atmospheres. Beyond this, the length of tube necessary makes it very inconvenient: in this case the following apparatus is used.

168. **Manometer with compressed air.**—The *manometer with compressed air* is founded on Boyle's law; it consists of a glass tube closed at the top, and filled with dry air. It is firmly cemented in a small iron box containing mercury. By a tubulure, A, in the side (fig. 120), this box is connected with the closed vessel containing the gas or vapour whose tension is to be measured.

In the graduation of this manometer, the quantity of air contained in the tube is such, that when the aperture A communicates freely with the

atmosphere, the level of the mercury is the same in the tube and in the tubulure. Consequently, at this level, the number 1 is marked on the scale to which the tube is affixed. As the pressure acting through the tubulure A increases, the mercury rises in the tube, until its weight, added to the tension of the compressed air, is equal to the external pressure.

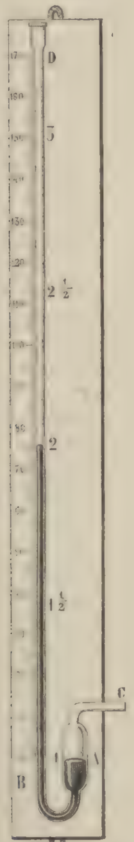


Fig. 119.

Fig. 120.

Fig. 121.

It would consequently be incorrect to mark two atmospheres in the middle of the tube; for since the volume of the air is reduced to one-half, its tension is equal to two atmospheres, and, together, with the weight of the mercury raised in the tube, is therefore more than two atmospheres. The position of the number is a little below the middle, at such a height that the elastic force of the compressed air, together with the weight of the mercury in the tube, is equal to two atmospheres. The exact position of

of the numbers 2, 3, 4, etc. on the manometer scale can only be determined by calculation. Sometimes this manometer is made of one glass tube, as represented in fig. 121. The principle is obviously the same.

169. **Regnault's barometric manometer.**—For measuring pressures of less than one atmosphere, M. Regnault has the following arrangement, which is a modification of his fixed barometer (fig. 112). In the same cistern dips a second tube *a*, of the same diameter, open at both ends, and provided at the top with a three-way cock, one of which is connected with an air pump and the other with the space to be exhausted. The farther the exhaustion is carried the higher the mercury rises in the tube *a*. The difference of level in the tubes *b* and *a* gives the pressure. Hence, by measuring the height *ab*, by means of the cathetometer, the pressure in the space that is being exhausted is accurately given. This apparatus is also called the *differential barometer.*

170. **Aneroid barometer.**—This instrument derives its name from the circumstance that no liquid is used in its construction (ἀ, without, νηρὸς, moist). Fig. 122 represents one of the forms of these instruments, constructed by Mr. Casella: it consists of a cylindrical metal box, exhausted of air, the top of which is made of thin corrugated metal, so elastic that it readily yields to alterations in the pressure of the atmosphere.

Fig. 122.

When the pressure increases, the top is pressed inwards ; when on the contrary it decreases, the elasticity of the lid, aided by a spring, tends to move it in the opposite direction. These motions are transmitted by delicate multiplying levers to an index which moves on a scale. The instrument is graduated empirically by comparing its indications under different pressures with those of an ordinary mercurial barometer.

The aneroid has the advantage of being portable, and can be constructed of such delicacy as to indicate the difference in pressure between the height of an ordinary table and the ground. It is hence much used in determining heights in mountain ascents. But it is liable to get out of order, especially when it has been subjected to great variations of pressure ; and its indications must from time to time be compared by means of a standard barometer.

171. **Laws of the mixture of gases.**—If a communication is opened between two closed vessels containing gases, they at once begin to mix,

whatever be their density, and in a longer or shorter time the mixture is complete, and will continue so, unless chemical action or some other extraneous cause intervene. The laws which govern the mixture of gases may be thus stated :—

I. *The mixture takes place rapidly and is homogeneous, that is, each portion of the mixture contains the two gases in the same proportion.*

II. *If the gases severally and the mixture have the same temperature, and if the gases severally and the mixture occupy the same volume, then the pressure per unit of area exerted by the mixture will equal the sum of the pressures per unit of area exerted by the gases severally.*

From the second law a very convenient formula can be easily deduced.

Let v_1, v_2, v_3 . . . . be the volumes of several gases under pressure of p_1, p_2, p_3 . . . . respectively. Suppose these gases when mixed to have a volume V, under a pressure P, the temperatures being the same. By Boyle's law we know that v_1 will occupy a volume V under a pressure p_1' provided

$$Vp_1' = v_1p_1$$

Similarly

$$Vp_2' = v_2p_2$$

and so on. But we learn from the above law that

$$P = p_1' + p_2' + \ \ldots$$

therefore

$$VP = v_1p_1 + v_2p_2 + v_3p_3 + \ \ldots$$

It obviously follows that if the pressures are all the same, the volume of the mixture equals the sum of the separate volumes.

The first law was shown experimentally by Berthollet, by means of an apparatus represented in fig. 123. It consists of two glass globes provided with stopcocks, which can be screwed one on the other. The upper globe was filled with hydrogen, and the lower one with carbonic acid, which has 22 times the density of hydrogen. The globes having been fixed together were placed in the cellars of the Paris Observatory and the stopcocks then opened, the globe containing hydrogen being uppermost. Berthollet found after some time that the pressure had not changed, and that, in spite of the difference in density, the two gases had become uniformly mixed in the two globes. Experiments made in the same manner with other gases gave the same results, and it was found that the diffusion was more rapid in proportion as the difference between the densities was greater.

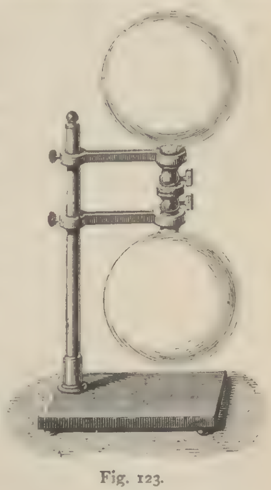


Fig. 123.

The second law may be demonstrated by passing into a graduated tube, over mercury, known volumes of gas at known pressures. The pressure and volume of the whole mixture are then measured, and found to be in accordance with the law.

Gaseous mixtures follow Boyle's law, like simple gases, as has been proved for air (163), which is a mixture of nitrogen and oxygen.

172. **Mixture of gases and liquids. Absorption.**—Water and many liquids possess the property of absorbing gases. Under the same conditions of pressure and temperature a liquid does not absorb equal quantities of different gases. At the ordinary temperature and pressure water dissolves $\frac{25}{1000}$ its volume of nitrogen, $\frac{46}{1000}$ its volume of oxygen, its own volume of carbonic acid, and 430 times its volume of ammoniacal gas.

The whole subject of gas absorption has been investigated by Bunsen, to whose work* the student is referred for further information. The general laws of gas-absorption are the following :—

I. *For the same gas, the same liquid, and the same temperature, the weight of gas absorbed is proportional to the pressure.* This may also be expressed by saying that at all pressures the volume dissolved is the same ; or that the density of the gas absorbed is in a constant relation with that of the external gas which is not absorbed.

Accordingly, when the pressure diminishes, the quantity of dissolved gas decreases. If a solution of gas be placed under the air pump and a vacuum created, the gas obeys its expansive force and escapes with effervescence.

II. *The quantity of gas absorbed is greater when the temperature is lower* ; that is to say, when the elastic force of the gas is less.

III. *The quantity of gas which a liquid can dissolve is independent of the nature and of the quantity of other gases which it may already hold in solution.*

In every gaseous mixture each gas exercises the same pressure as it would if its volume occupied the whole space ; and the total pressure is equal to the sum of the individual pressures. When a liquid is in contact with a gaseous mixture, it absorbs a certain part of each gas, but less than it would if the whole space were occupied by each gas. The quantity of each gas dissolved is proportional to the pressure which the unabsorbed gas exercises alone. For instance, oxygen forms only about $\frac{1}{5}$ the quantity of air ; and water, in ordinary conditions, absorbs exactly the same quantity of oxygen as it would if the atmosphere were entirely formed of this gas, under a pressure equal to $\frac{1}{5}$ that of the atmosphere.

CHAPTER III.

PRESSURE ON BODIES IN AIR. BALLOONS.

173. **Archimedes' principle applied to gases.**—The pressure exerted by gases on bodies immersed in them is transmitted equally in all directions, as has been shown by the experiment with the Magdeburg hemi-

* Gasometric Methods, by R. Bunsen, translated by Prof. Roscoe. Walton and Maberly.

pheres. It therefore follows that all which has been said about the equilibrium of bodies in liquids applies to bodies in air ; they lose a part of their weight equal to that of the air which they displace.

The loss of weight in air is demonstrated by means of the *baroscope*, which consists of a scalebeam, at one of whose extremities a small leaden weight is supported, and at the other there is a hollow copper sphere (fig. 124). In the air they exactly balance one another; but when they are placed under the receiver of the air pump and a vacuum is produced, the sphere sinks ; thereby showing that in reality it is heavier than the small leaden weight. Before the air is exhausted each body is buoyed up by the weight of the air which it displaces. But as the sphere is much the larger of the two, its weight undergoes most apparent diminution, and thus, though in reality the heavier body, it is balanced by the small leaden weight. It may be proved by means of the same apparatus that this loss is equal to the weight of the displaced air. Suppose the volume of the sphere is 10 cubic inches. This weight of this volume of air is 3·1 grains. If now this weight be added to the leaden weight, it will overbalance the sphere in air, but will exactly balance it in vacuo.

Fig. 124.

The principle of Archimedes is true for bodies in air ; all that has been said about bodies immersed in liquids applies to them, that is, that when a body is heavier than air, it will sink, owing to the excess of its weight over the buoyancy. If it is as heavy as air, its weight will exactly counterbalance the buoyancy, and the body will float in the atmosphere. If the body is lighter than air, the buoyancy of the air will prevail, and the body will rise in the atmosphere until it reaches a layer of the same density as its own. The force of the ascent is equal to the excess of the buoyancy over the weight of the body. This is the reason why smoke, vapours, clouds, and air balloons rise in the air.

AIR BALLOONS.

174. **Air balloons.**—*Air balloons* are hollow spheres made of some light impermeable material, which, when filled with heated air, with hydrogen gas, or with coal gas, rise in the air in virtue of their relative lightness.

They were invented by the brothers Mongolfier, of Annonay, and the first experiment was made at that place in June 1783. Their balloon was a sphere of 40 yards in circumference, and weighed 500 pounds.

At the lower part there was an aperture, and a sort of boat was suspended, in which fire was lighted to heat the internal air. The balloon rose to a height of 2,200 yards, and then descended without any accident.

Charles, a professor of physics in Paris, substituted hydrogen for hot air. He himself ascended in a balloon of this kind in December 1783. The use of hot air balloons was entirely given up in consequence of the serious accidents to which they were liable.

Since then, the art of ballooning has been greatly extended, and many ascents have been made. That which Guy Lussac made in 1804 was the most remarkable for the facts with which it has enriched science, and for the height which he attained—23,000 feet above the sea level. At this height the barometer descended to 12·6 inches, and the thermometer, which was 31° C. on the ground, was 9 degrees below zero.

In these high regions, the dryness was such on the day of Gay-Lussac's ascent, that hygrometric substances, such as paper, parchment, etc., became dried and crumpled as if they had been placed near the fire. The respiration and circulation of the blood were accelerated in consequence of the great rarefaction of the air. Gay-Lussac's pulse made 120 pulsations in a minute, instead of 66, the normal number. At this great height the sky had a very dark blue tint, and an absolute silence prevailed.

One of the most remarkable of recent ascents was made by Mr. Glaisher and Mr. Coxwell, in a large balloon belonging to the latter. This was filled with 90,000 cubic feet of coal gas (sp. gr. 0·37 to 0·33) ; the weight of the load was 600 pounds. The ascent took place at 1 p.m. on September 5, 1861 ; at 1° 28′ they had reached a height of 15,750 feet, and in eleven minutes after a height of 21,000 feet, the temperature being $-10{\cdot}4$; at 1° 50′ they were at 26,200 feet, with the thermometer at $-15{\cdot}2°$. At 1° 52′ the height attained was 29,000 feet, and the temperature $-16{\cdot}0$ C. At this height the rarefaction of the air was so great, and the cold so intense, that Mr. Glaisher fainted, and could no longer observe. According to an approximate estimation the lowest barometric height they attained was 7 inches, which would correspond to an elevation of 36,000 to 37,000 feet.

175. **Construction and management of balloons.**—A balloon is made of long bands of silk sewed together and covered with caoutchouc varnish, which renders it air-tight. At the top there is a safety valve closed by a spring, which the aëronaut can open at pleasure, by means of a cord. A light wicker-work boat is suspended by means of cords to a net-work, which entirely covers the balloon.

A balloon of the ordinary dimensions, which can carry three persons, is about 16 yards high, 12 yards in diameter, and its volume when it is quite full is about 680 cubic yards. The balloon itself weighs 200 pounds ; the accessories, such as the rope and boat, 100 pounds.

The balloon is filled either with hydrogen or with coal gas. Although the latter is heavier than the former, it is generally preferred, because it is cheaper and more easily obtained. It is passed into the balloon from the gas reservoir by means of a flexible pipe. It is important not to fill the balloon quite full, for the atmospheric pressure diminishes as it rises (fig. 125), and the gas inside expanding in consequence of its elastic force,

tends to burst it. It is sufficient for the ascent if the weight of the displaced air exceeds that of the balloon by 8 or 10 pounds. And this force remains constant so long as the balloon is not quite distended by the dilatation of the air in the interior. If the atmospheric pressure, for example, has diminished to one-half, the gas in the balloon, according to Boyle's law, has doubled its volume. The volume of the air displaced is therefore twice as great; but, since its density has become only one-half, the weight, and consequently the upward buoyancy, are the same. When once the balloon is completely dilated, if it continue to rise the force of the ascent decreases, for the volume of the displaced air remains the same, but its density diminishes, and a time arrives at which the buoyancy is equal to the weight of the balloon. The balloon can now only take a horizontal direction, carried by the currents of air which prevail in the atmosphere. The aëronaut knows by the barometer whether he is ascending or descending; and by the same means he determines the height which he has reached. A long flag fixed to the boat would indicate, by the position it takes either above or below, whether the balloon is descending or ascending.

Fig. 125.

When the aëronaut wishes to descend, he opens the valve at the top of the balloon by means of the cord, which allows gas to escape, and the balloon sinks. If he wants to descend more slowly, or to rise again, he empties out bags of sand, of which there is an ample supply in the car. The descent is facilitated by means of a grappling iron fixed to the boat. When once this is fixed to any obstacle, the balloon is lowered by pulling the cord.

The only practical applications which air balloons have hitherto had have been in military reconnoitring. At the battle of Fleurus, in 1794, a captive balloon, that is, one held by a cord, was used, in which there was an observer who reported the movements of the enemy by means of signals. At the battle of Solferino the movements and dispositions of the Austrian troops were watched by a captive balloon; and in the war in America balloons were frequently used, while their importance during the siege of

Paris is fresh in all memories. The whole subject of military ballooning has been treated in two papers by Lieut. Groves and by Captain Beaumont, in a recent volume of the Professional Papers of the Royal Engineers. Many ascents have recently been made by Mr. Glaisher for the purpose of making meteorological observations in the higher regions of the atmosphere. Air balloons can only be truly useful when they can be guided, and as yet all attempts made with this view have completely failed. There is no other course at present than to rise in the air until there is a current which has more or less the desired direction.

Fig. 126.

176. **Parachute.**—The object of the parachute is to allow the aëronaut to leave the balloon, by giving him the means of lessening the rapidity of his descent. It consists of a large circular piece of cloth (fig. 126) about 16 feet in diameter, and which by the resistance of the air spreads out like a gigantic umbrella. In the centre there is an aperture, through which the air compressed by the rapidity of the descent makes its escape; for otherwise oscillations might be produced, which, when communicated to the boat, would be dangerous.

In fig. 125 there is a parachute attached to the net-work of the balloon by means of a cord which passes round a pulley, and is fixed at the other end to the boat. When the cord is cut the parachute sinks, at first very rapidly, but more slowly as it becomes distended, as represented in the figure.

177. **Calculation of the weight which a balloon can raise.**—To calculate the weight which can be raised by a balloon of given dimensions let us suppose it perfectly spherical, and premise that the formulæ which express the volume and the superficies in terms of the radius are $V = \frac{4\pi R^3}{3}$ and $S = 4\pi R^2$, π being the ratio of the circumference to the diameter, and equal to 3·1416. The radius R being measured in feet, let p be, in pounds, the weight of a square foot of the material of which the balloon is constructed; let P be the weight of the car and the accessories, a the weight in pounds of a cubic foot of air at zero, and under the pressure 0·76, and a the weight of the same volume under the same conditions of the gas with which the balloon is inflated (141). Then the

total weight of the envelope in pounds will be $4\pi R^2 p$; that of the gas will be $\frac{4\pi R^3 a'}{3}$, and that of the displaced air $\frac{4\pi R^3 a}{3}$. If X be the weight which the balloon can support, we have $X = \frac{4\pi R^3 a}{3} - \frac{4\pi R^3 a'}{3} - 4\pi R^2 p - P$. Whence

$$X = \frac{4\pi R^3}{3}(a - a') - 4\pi R^2 - P.$$

But, as we have before seen (175), in order that the balloon may rise, the weights must be less by 8 or 10 pounds than that given by this equation.

CHAPTER IV.

APPARATUS FOUNDED ON THE PROPERTIES OF AIR.

178. **Air pump.**—The air pump is an instrument by which a vacuum can be produced in a given space, or rather by which air can be greatly rarefied, for an absolute vacuum cannot be produced by its means. It

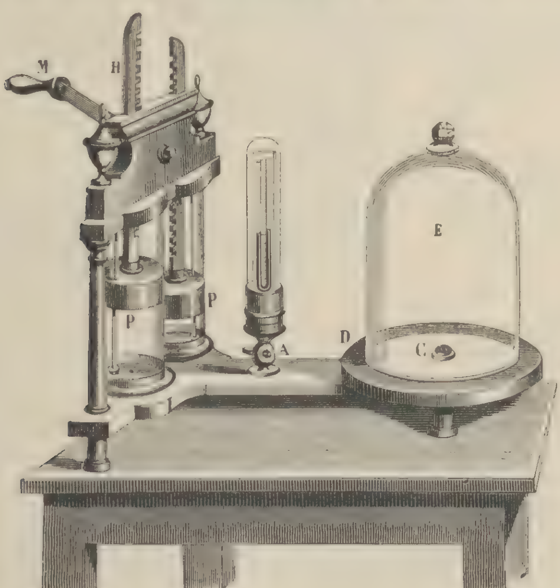


Fig. 127.

was invented by Otto von Guericke in 1650, a few years after the invention of the barometer.

The air pump, as now usually constructed, may be described as follows: In fig. 127, which shows the general arrangement, E is the *receiver*, in which the vacuum is to be produced. It is a bell glass, resting on a plate D, of thick glass ground perfectly smooth. In the centre of D, at C, there is an opening by which a communication is made between the interior of the receiver and of the cylinders P, P. This communication is effected by a tube or pipe passing through the body of the plate A, and then branching off at right angles, as shown by K*co*, K*cs*, in fig. 128, which represents a horizontal section of the machine. In the cylinders—which are commonly of glass, and which are firmly cemented to the plate A—are two pistons, P and Q, fitting air-tight. Each piston is moved by a rack, working with a pinion, H, turned by a handle, M. This is shown more plainly in fig. 129, which represents a vertical section of the machine through the cylinders: here H is the pinion, and MN the handle. When

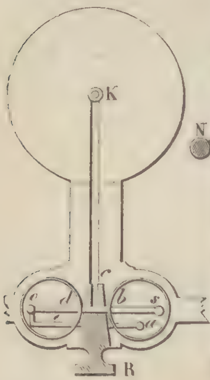


Fig. 128.

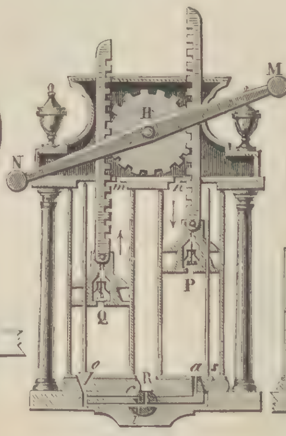


Fig. 129.

Fig. 130.

M is forced down one piston is raised, and the other depressed. When M's action is reversed, the former piston is depressed, and the latter raised.

The action of the machine is this: Each cylinder is fitted with a valve so contrived that when its piston is raised, communication is opened between the cylinder and the receiver : when it is depressed the communication is closed. Now if P were simply raised, a vacuum would be formed below P ; but as a communication is opened with the receiver E, the air in E expands so as to fill both the receiver and the cylinder. As soon as the piston begins to descend, the communication is closed, and none of the air in the cylinder returns to the receiver, but, by means of properly constructed valves, escapes into the atmosphere. Consequently the rarefaction which the air in the receiver has undergone is permanent. By the next stroke a further rarefaction is produced ; and so on, at each succeeding stroke.

It is plain that when the rarefaction has proceeded to a considerable extent the atmospheric pressure on the top of P will be very great, but it will be very nearly balanced by the atmospheric pressure on the top of the other piston. Consequently the experimenter will have to overcome only the difference of the two pressures. It is for this reason that two cylinders are employed.

To explain the action of the valves we must go into particulars. The general arrangement of the interior of the cylinders is shown in fig. 129. Fig. 132 shows the section of the piston in detail. The piston is formed of two brass discs (X and V), screwed to one another, and compressing between them a series of leathern discs Z, whose diameters are slightly greater than those of the brass discs. The leather is thoroughly saturated with oil, so as to slide air-tight, though with but little friction, within the cylinder. To the centre of the upper disc is screwed a piece, B, to which the rack H is riveted. The piece B is pierced so as to put the interior of the cylinder into communication with the external air. This communication is closed by a valve *t*, held down by a delicate spring, *r*. When the piston is moved downward the air below the piston is compressed until it forces up *t* and escapes. The instant the action is reversed, the valve *t* falls, and is held down by the spring, and the pressure of the external air, which is thereby kept from coming in. The communication between the cylinder below the piston and the receiver is opened and closed by the valve marked *o* in fig. 129, and *sg* in fig. 132. The rod *sg* passing through the piston is held by friction, and is raised with it; but is kept from being lifted through more than a very small distance by the top of the cylinder, while the piston, in continuing its upward motion, slides over *sg*. When the piston descends it brings the valve with it, which at once cuts off the communication between the cylinder and the receiver.

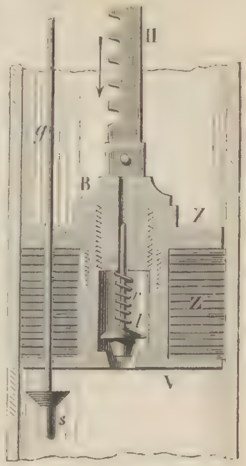


Fig. 132.

179. **Air pump gauge.**—When the pump has been worked some time, the pressure in the receiver is indicated by the difference of level of the mercury in the two legs of a glass tube bent like a syphon, one of which is opened, and the other closed like the barometer. This little apparatus, which is called the *gauge*, is fixed to an upright scale, and placed under a small bell jar, which communicates with the receiver E by a stop-cock, A, inserted in the tube leading from the orifice C to the cylinders, fig. 127.

Before commencing to exhaust the air in the receiver, its elastic force exceeds the weight of the column of mercury, which is in the closed branch and which consequently remains full. But as the pump is

worked, the elastic force soon diminishes, and is unable to support the weight of the mercury, which sinks and tends to stand at the same level in both legs. If an absolute vacuum could be produced, they would be exactly on the same level, for there would be no pressure either on the one side or the other. But with the very best machines the level is always about a thirtieth of an inch higher in the closed branch, which indicates that the vacuum is not absolute, for the elastic force of the residue is equal to the pressure of a column of mercury of that height.

Practically the machine can never give an absolute vacuum, for, as we have seen, the air becomes ultimately so rarefied that, when the pistons are at the bottom of the cylinder, its elastic force cannot overcome the pressure on the valves in the inside of the piston, which, therefore, do not open.

Theoretically an absolute vacuum is also impossible; for, since the volume of each cylinder is, say, $\frac{1}{20}$ that of the receiver, only $\frac{1}{21}$ of the air in the receiver is extracted at each stroke of the piston, and consequently it is impossible to exhaust all the air which it contains. The theoretical degree of exhaustion after a given number of strokes is easily calculated as follows:—Let A denote the volume of the receiver, including in that term the pipe; B the volume of the cylinder between the highest and lowest positions of the piston; and assume for the sake of distinctness that there is only one cylinder; then the air which occupied A before the piston is lifted occupies A + B after it is lifted, and consequently if D_1 is the density at the end of the first stroke and D the original density, we must have

$$D_1 = D\frac{A}{A+B}$$

If D_2 is the density at the end of the second stroke, we have for just the same reason

$$D_2 = D_1\frac{A}{A+B} = D\left(\frac{A}{A+B}\right)^2$$

Now this reasoning will apply to *n* strokes;

consequently $$D_n = D\left(\frac{A}{A+B}\right)^n$$

If there are two equal cylinders, the same formula holds, but in this case, in counting *n*, upstrokes and downstrokes equally reckon as *one*.

It is obvious that the exhaustion is never complete, since D_n can be zero only when *n* is infinite. However, a number of strokes not excessively great would render the exhaustion virtually complete, even if A is several times greater than B. Thus if A = 10 B, a hundred strokes will reduce the density from D to 0·0004 D; that is, if the initial pressure is 30 in., the pressure at the end of 100 strokes is 0·012 of an inch.

Practically, however, a limit is placed on the rarefaction that can be produced by any given machine; for, as we have seen, the air becomes ultimately so rarefied that, when the pistons are at the bottom of the cylinder, its elastic force cannot overcome the pressure on the valves in

the inside of the piston; they therefore do not open, and there is no further action of the machine.

180. **Doubly-exhausting stopcock.**—M. Babinet has invented an improved stopcock, by which the exhaustion of the air can be carried to a very high degree. This stopcock is placed in the fork of the pipe leading from the receiver to the two cylinders; it is perforated by several channels, which are successively used by turning it into two different positions. Fig. 128 represents a horizontal section of the stopcock R, in such a position that, by its central opening and two lateral openings, it forms a communication between the orifice K of the plate, and the two valves *o* and *s*. The machine then works as has been described. In fig. 131 the stopcock has been turned a quarter, and the transversal channel *db*, which was horizontal in fig. 128, is now vertical, and its extremities are closed by the side of the hole in which the stopcock works. But a second channel, which was closed before, and which has taken the place of the first, now places the right cylinder *alone* in communication with the receiver by the channel *cbs* (fig. 131), and it further connects the right with the left cylinder by a channel, *aeo* (fig. 131), or *aico* (fig. 130). This channel passes from a central opening, *a*, placed at the base of the right cylinder, across the stopcock to the valve *o* of the other cylinder, as represented in figs. 130 and 131; but this channel is closed by the stopcock when it is in its first position, as is seen in figs. 128 and 129.

The right piston in rising exhausts the air of the receiver, but when it descends the exhausted air is driven into the left cylinder through the orifice *a*, the channel *io*, and the valve *o* (fig. 130), which is open. When the same piston rises, that of the left sinks; but the air which is above it does not return into the right cylinder, because the valve *o* is now closed. As the right cylinder continues to exhaust the air in the receiver, and to force it into the left cylinder, the air accumulates here, and ultimately acquires sufficient tension to raise the valve of the piston Q, which was impossible before the stopcock was turned, for it is only when the valves in the piston no longer open, that a quarter of a turn is given to the stopcock.

181. **Bianchi's air pump.**—M. Bianchi has invented an air pump which has several advantages. It is made entirely of iron, and it has only one cylinder, which oscillates in a horizontal axis fixed at its base, as seen in fig. 133. A horizontal shaft, with heavy fly-wheel, V, works in a frame, and is turned by a handle, M. A crank, *m*, which is joined to the top of the piston-rod, is fixed to the same shaft, and consequently at every revolution of the wheel the cylinder makes two oscillations.

In some cases, as in that shown in the figure, the crank and the fly-wheel are on parallel axes connected by a pair of cog-wheels. The modification in the action produced by this arrangement is as follows:—If the cog-wheel on the former axis has twice as many teeth as that on the latter axis, the pressure which raises the piston is doubled: an advantage which is counterbalanced by the inconvenience that now the piston will make one oscillation for one revolution of the fly-wheel.

The machine is double acting; that is, the piston PP (fig. 134) produces a vacuum both in ascending and descending, This is effected by the following arrangements: In the piston there is a valve, *b*, opening upwards as in the ordinary machine. The piston rod AA is hollow, and in the inside there is a copper tube, X, by which the air makes its escape through the valve *b*. At the top of the cylinder there is a second valve,

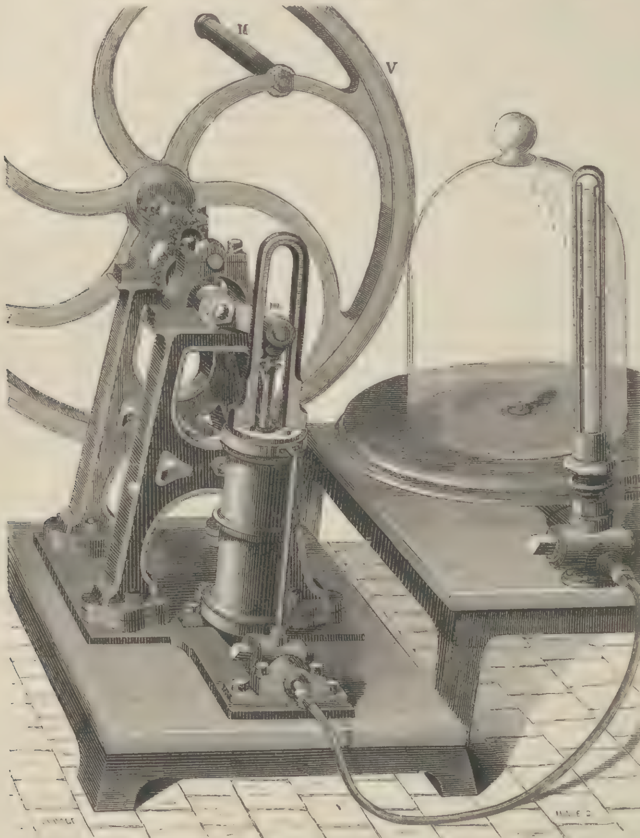


Fig. 133.

a, opening upwards. An iron rod, D, works with gentle friction in the piston, and terminates at its ends in two conical valves, *s* and *s'*, which fit into the openings of the tube BC leading to the receiver.

Let us suppose the piston descends. The valve *s'* is then closed, and the valve *s* being open, the air of the receiver passes in the space above the piston, while the air in the space below the piston undergoes com-

pression, and raising the valve, escapes by the tube X, which communicates with the atmosphere. When the piston ascends, the exhaustion takes place through *s'*, and the valve *s* being closed, the compressed air escapes by the valve *a*.

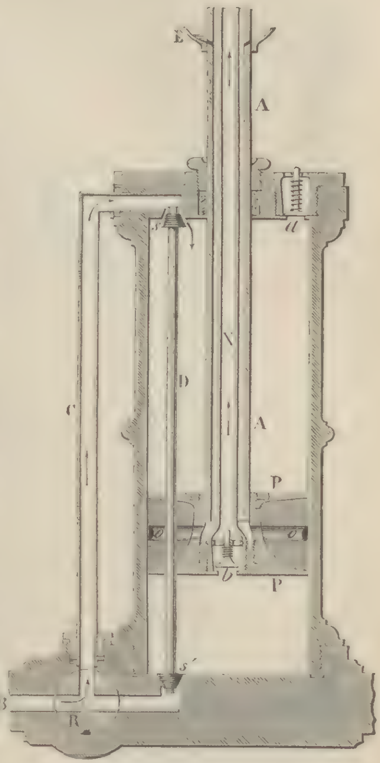


Fig. 134.

The machine has a stopcock for double exhaustion, similar to that already described (180). It is also oiled in an ingenious manner. A cup, E, round the rod is filled with oil, which passes into the annular space between the rod AA and the tube X; it passes then into a tube *oo*, in the piston, and forced by the atmospheric pressure, is uniformly distributed on the surface of the piston.

The apparatus is of iron, and can consequently be made of much greater dimensions than the ordinary machine. A vacuum can also be produced with it in far less time and in larger apparatus.

182. **Sprengel's air pump.**—Sprengel has devised a form of air pump which depends on the principle of converting the space to be exhausted into a Torricellian vacuum. The idea and construction of the apparatus are thus described by the inventor.

If an aperture be made in the top of a barometer tube, the mercury sinks and draws in air; if the experiment be so arranged as to allow air to enter along with mercury, and the supply of air is limited while that of mercury is unlimited, the air will be carried away, and a vacuum produced. The following is the simplest form of the apparatus in which this action is realised. In fig. 135 *cd* is a glass tube longer than a barometer, open at both ends, and connected by means of india-rubber tubing with a funnel, A, filled with mercury and supported by a stand. Mercury is allowed to fall in this tube at a rate regulated by a clamp at *c*; the lower end of the tube *cd* fits in the flask B, which has a spout at the side a little higher than the lower end of *cd*; the upper part has a branch at *x* to which a receiver R can be tightly fixed. When the clamp at *c* is opened, the first portion

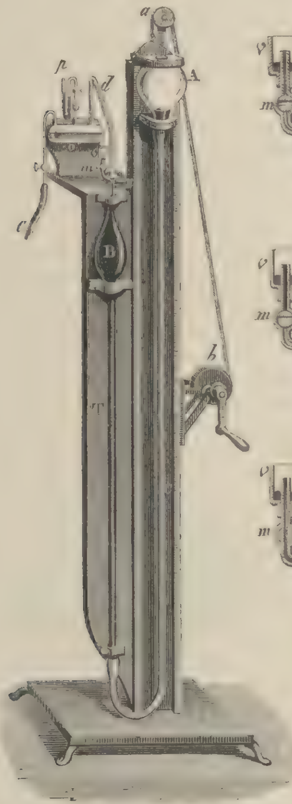
of mercury which runs out closes the tube and prevents air from entering below. As the mercury is allowed to run down, the exhaustion begins, and the whole length of the tube from x to d is filled with cylinders of air and mercury having a downward motion. Air and mercury escape through the spout of the bulb B which is above the basin A, where the mercury is collected. It is poured back from time to time into the funnel A, to be repassed through the tube until the exhaustion is complete. As this point is approached, the enclosed air between the mercury cylinders is seen to diminish, until the lower part of *cd* forms a continuous column of mercury about 30 inches high. Towards this stage of the process a noise is heard like that of a water hammer when shaken; the operation is completed when the column of mercury encloses no air, and a drop of mercury falls on the top of the column without enclosing the slightest air bubble. The height of the column then represents the height of the column of mercury in the barometer; in other words, it is a barometer whose Torricellian vacuum is the receiver R. This apparatus has been used with great success in experiments in which a very complete exhaustion is required, as in the preparation of Geissler's tubes. (See Book X. Chapter VI.) It may be advantageously combined with an exhausting syringe which removes the greater part of the air, the exhaustion being then completed as above.

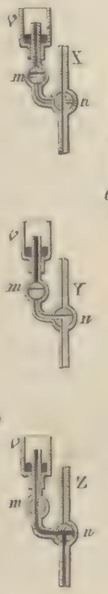
Fig. 135.

183. **Morren's mercury pump.**—Figs. 136 and 137 represent a mercurial air pump, which is an improvement by Alvergnat, of a form devised by Morren.

It consists of two reservoirs, A and B, figs. 136 and 137, connected by a barometer tube T, and a long caoutchouc tube C. The reservoir B and the tube T are fixed to a vertical support A, which is movable and open, and can be alternately raised and lowered through a distance of nearly four feet. This is effected by means of a long wire rope, which is fixed at one end to the reservoir A, and passes over two pulleys, a and b, the latter

of which is turned by a handle. Above the reservoir B is a three-way cock n; to this is attached a tube d, for exhaustion, and on the left is an ordinary stopcock m, which communicates with a reservoir of mercury v, and with the air. The exhausting tube d is not in direct communication with the receiver to be exhausted: it is first connected with a reservoir o, partially filled with sulphuric acid, and designed to dry the gases which enter the apparatus. A caoutchouc tube, c, makes communication with





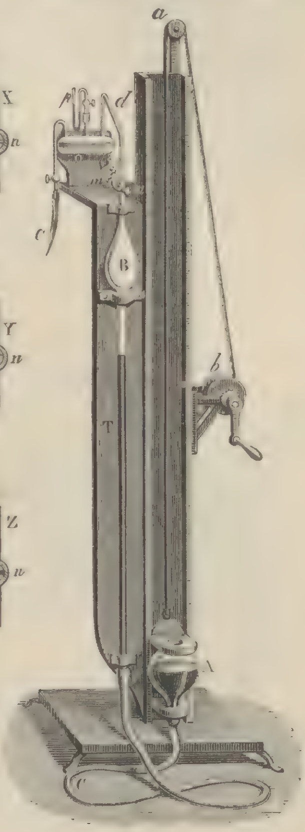


Fig. 136. Fig. 137.

the receiver which is to be exhausted. On the reservoir o is a small mercury manometer p.

These details being understood, suppose the reservoir A at the top of its course (fig. 136), the stopcock m open, and the stopcock n turned as seen in Z; the caoutchouc tube, the tube T, the reservoir B, and the tube above, are filled with mercury as far as v; closing then the stopcock m, and lowering the reservoir A (fig. 137), the mercury sinks in the

reservoir B, and in the tube T, until the difference of levels in the two tubes is equal to the barometric height, and there is a vacuum in the reservoir B. Turning now the stopcock *n*, as shown in figure X, the the gas from the space to be exhausted passes into the barometric chamber B, by the tubes *c* and *d*, and the level again sinks in the tube T. The stopcocks are now replaced in the first position (fig. Z), and the reservoir A is again lifted, the excess of pressure of mercury in the caoutchouc tube expels through the stopcocks, *n* and *m*, the gas which had passed into the chamber B, and if a few droplets of mercury are carried along with them they are collected in the vessel *v*. The process is repeated until the mercury is virtually at the same level in both legs.

Like Sprengel's pump this is very slow in its working, and like it is best employed in completing the exhaustion of a space which has already been partially rarefied; for a vacuum of $\frac{1}{10}$ of a millimeter may be obtained by its means.

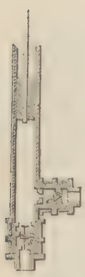


Fig. 138.

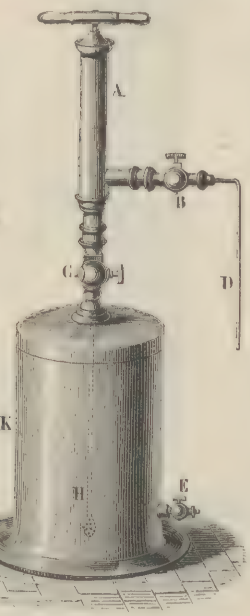


Fig. 139.

184. **Condensing pump.**—The condensing pump is an apparatus for compressing air, or any other gas. The form usually adopted is the following: In a cylinder, A, of small diameter (fig. 139), there is a solid piston, the rod of which is moved by the hand. The cylinder is provided with a screw which fits into the receiver K. Fig. 138 shows the arrangement of the valves, which are so constructed that the lateral valve *o* opens from the outside, and the lower valve *s* from the inside.

When the piston descends, the valve *o* closes, and the elastic force of the compressed air opens the valve *s*, which thus allows the compressed air to pass into the receiver. When the piston ascends, *s* closes and *o* opens, and permits the entrance of fresh air, which in turn becomes compressed by the descent of the piston, and so on.

This apparatus is chiefly used for charging liquids with gases. For this purpose the stopcock B is connected with a reservoir of the gas, by means of the tube D. The pump exhausts this gas, and forces it into the vessel K, in which the liquid is contained. The artificial gaseous waters are made by means of analogous apparatus.

185. **Uses of the air pump.**—A great many experiments with the air pump have been already described. Such are the mercurial rain

(13), the fall of bodies in vacuo (68), the bladder (139), the bursting of a bladder (145), the Magdeburg hemispheres (146), and the baroscope (173).

The *fountain in vacuo* (fig. 140) is an experiment made with the air pump, and shows the elastic force of the air. It consists of a glass globe, A, provided at the bottom with a stopcock, and a tubulure which projects into the interior. Having screwed this apparatus to the air pump it is exhausted, and, the stopcock being closed, it is placed in a vessel of water, R. Opening then the stopcock the atmospheric pressure upon the water in the vessel makes it jet through the tubulure into the interior of the vessel as shown in the drawing.

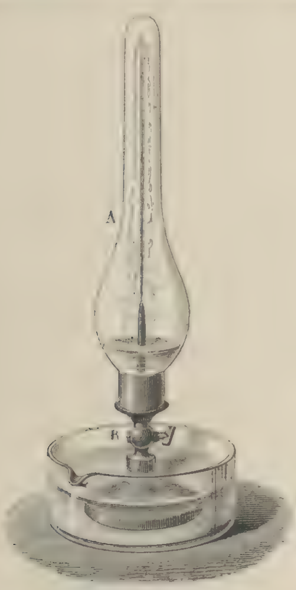


Fig. 140.

Fig. 141.

Fig. 141 represents an experiment illustrating the effect of atmospheric pressure on the human body. A glass vessel, open at both ends, being placed on the plate of the machine, the upper end of the cylinder is closed by the hands, and a vacuum is made. The hand then becomes pressed by the weight of the atmosphere, and can only be taken away by a great effort. And as the elasticity of the fluids contained in the organs is not counterbalanced by the weight of the atmosphere, the palm of the hand swells, and blood tends to escape from the pores.

By means of the air pump it may be shown that air, by reason of the oxygen it contains, is necessary for the support of combustion and of life. For if we place a lighted taper under the receiver, and begin to exhaust the air, the flame becomes weaker as rarefaction proceeds, and is finally extinguished. Similarly an animal faints and dies, if a vacuum is formed

in a receiver under which it is placed. Mammalia and birds soon die in vacuo. Fish and reptiles support the loss of air for a much longer time. Insects can live several days in vacuo.

Substances liable to ferment may be kept in vacuo for a long time without alteration, as they are not in contact with oxygen, which is necessary for fermentation. Food kept in hermetically-closed cases, from which the air had been expelled, has been found as fresh after several years as on the first day.

186. **Hero's fountain.**—Hero's fountain, which derives its name from its inventor, Hero, who lived at Alexandria, 120 B.C., depends on the elasticity of the air. It consists of a brass dish, D (fig. 142), and of two

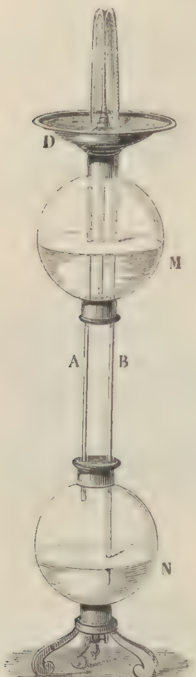


Fig. 142.

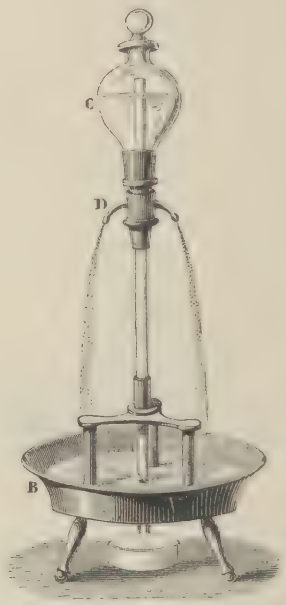


Fig. 143.

glass globes, M and N. The dish communicates with the lower part of the globe N by a long copper tube, B; and another tube, A, connects the two globes. A third tube passes through the dish to the lower part of globe M. This tube having been taken out, the globe M is partially filled with water, the tube is then replaced, and water is poured into the dish. The water flows through the tube B into the lower globe, and expels the air, which is forced into the upper globe; the air, thus compressed, acts upon the water, and makes it et out as represented in the figure. If it were not for the resistance of the atmosphere and friction,

the liquid would rise to a height above the water in the dish equal to the difference of the level in the two globes.

187. **Intermittent fountain.**—The *intermittent fountain* depends partly on the elastic force of the air and partly on the atmospheric pressure. It consists of a stoppered glass globe (C, fig. 143), provided with two or three capillary tubulures, D. A glass tube open at both ends reaches at one end to the upper part of the globe C; the other end terminates just above a little aperture in the dish B, which supports the whole apparatus.

The water with which the globe C is nearly two-thirds filled, runs out by the tubes D, as shown in the figure; the internal pressure at D being equal to the atmospheric pressure, together with the weight of the column of water CD, while the external pressure at that point is only that of the atmosphere. These conditions prevail so long as the lower end of the glass tube is open, that is, so long as air can enter C and keep the air in C at the same density as the external air; but the apparatus is arranged so that the orifice in the dish B does not allow so much water to flow out as it receives from the tubes D, in consequence of which the level gradually rises in the dish, and closes the lower end of the glass tube. As the external air cannot now enter the globe C, the air becomes rarefied in proportion as the flow continues, until the pressure of the column of water CD, together with the tension of the air contained in the globe, is equal to this external pressure at D: the flow consequently stops. But as water continues to flow out of the dish, the tube A becomes open again, air enters, and the flow recommences, and so on, as long as there is water in the globe C.

188. **The syphon.**—The syphon is a bent tube open at both ends and with unequal legs (fig. 144). It is used in transferring liquids in the

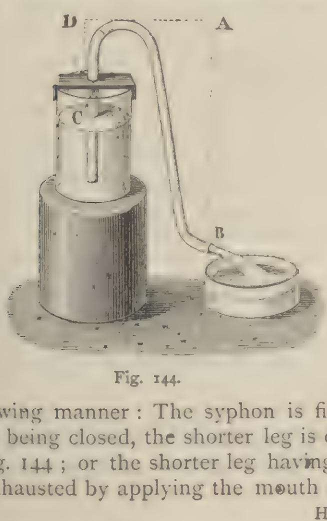


Fig. 144.

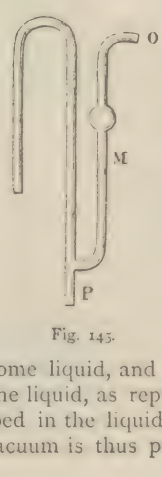


Fig. 145.

following manner: The syphon is filled with some liquid, and the two ends being closed, the shorter leg is dipped in the liquid, as represented in fig. 144; or the shorter leg having been dipped in the liquid, the air is exhausted by applying the mouth at B. A vacuum is thus produced,

the liquid in C rises and fills the tube in consequence of the atmospheric pressure. It will then run out through the syphon as long as the shorter end dips in the liquid.

A syphon of the form represented in fig. 145 is used where the presence of the liquid in the mouth would be objectionable. A tube, M, is attached to the longer branch, and it is filled by closing the end P, and sucking at O. An enlargement, M, renders the passage of any liquid into the mouth more difficult.

To explain this flow of water from the syphon, let us suppose it filled and the short leg immersed in the liquid. The pressure then acting on C, and tending to raise the liquid in the tube, is the atmospheric pressure minus the height of the column of liquid DC. In like manner, the pressure on the end of the tube, B, is the weight of the atmosphere less the pressure of the column of liquid AB. But as this latter column is longer than CD, the force acting at B is less than the force acting at C, and consequently a flow takes place proportional to the difference between these two forces. The flow will therefore be more rapid in proportion as the difference of level between the aperture B and the surface of the liquid in C is greater.

It follows from the theory of the syphon that it would not work in vacuo, nor if the height CD were greater than that of a column of liquid which counterbalances the atmospheric pressure.

189. **The intermittent syphon.**—In the intermittent syphon the flow is not continuous. It is arranged in a vessel, so that the shorter leg is near the bottom of the vessel, while the longer leg passes through it (fig. 146). Being fed by a constant supply of water, the level gradually rises both in the vessel and in the tube to the top of the syphon, which it fills, and water begins to flow out. But the apparatus is arranged so that the flow of the syphon is more rapid than that of the tube which supplies the vessel, and consequently the level sinks in the vessel until the shorter branch no longer dips in the liquid; the syphon is then empty, and the flow ceases. But as the vessel is continually fed from the same source, the level again rises, and the same series of phenomena is reproduced.

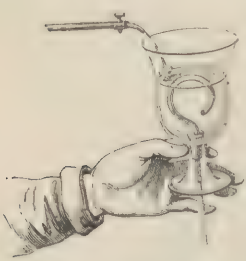


Fig. 146.

The theory of the intermittent syphon explains the natural intermittent springs which are found in many countries, and of which there is an excellent example near Giggleswick in Yorkshire. Many of these springs furnish water for several days or months, and then, after stopping for a certain interval, again recommence. In others the flow stops and recommences several times in an hour.

These phenomena are explained by assuming that there are subterranean fountains, which are more or less slowly filled by springs, and which are then emptied by fissures so occurring in the ground as to form an intermittent syphon.

190. **Different kinds of pumps.**—*Pumps* are machines which serve to raise water either by suction, by pressure, or by both efforts combined : they are consequently divided into *suction or lift pumps*, *force pumps*, and *suction and forcing pumps*.

The various parts entering into the construction of a pump are the barrel, the piston, the valves, and the pipes. The *barrel* is a cylinder of metal or of wood, in which is the piston. The latter is a metal or wooden cylinder wrapped with tow, and working with gentle friction the whole length of the barrel.

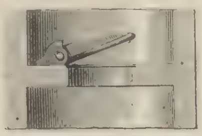


Fig. 147.

Fig. 148.

The valves are discs of metal or leather, which alternately close the apertures which connect the barrel with the pipes. The most usual valves are the *clack valve* (fig. 147) and the *conical valve* (fig. 148). The first is a metal disc fixed to a hinge on the edge of the orifice to be closed. In order more effectually to close it, the lower part of the disc is covered with thick leather. Sometimes the valve consists merely of a leather disc, of larger diameter than the orifice, nailed on the edge of the orifice. Its flexibility enables it to act as a hinge.

The conical valve consists of a metal cone fitting in an aperture of the same shape. Below this is an iron loop, through which passes a bolt-head fixed to the valve. The object of this is to limit the play of the valve when it is raised by the water, and to prevent its removal.

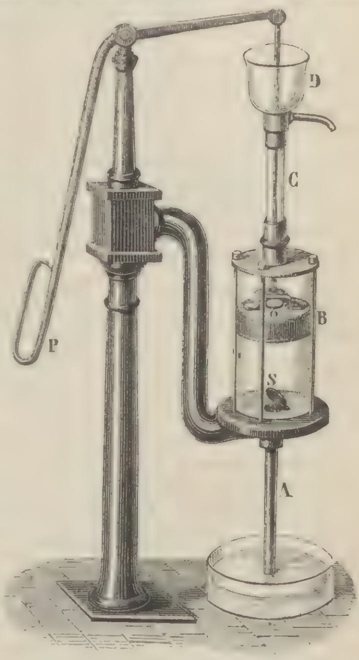


Fig. 149.

191. **Suction pump.**—Fig. 149 represents a model of a suction pump such as is used in lectures, but which has the same arrangement as the pumps in common use. It consists, 1st, of a *glass cylinder*, B, at the bottom of which there is a valve, S, opening upwards ; 2nd, of a *suction tube*, A, which dips into the reservoir from which water is

to be raised; 3rd, of a *piston*, which is moved up and down by a rod worked by a handle, P. The piston is perforated by a hole; the upper aperture is closed by a valve, O, opening upwards.

When the piston rises from the bottom of the cylinder, a vacuum is produced below, and the valve O is kept closed by the atmospheric pressure, while the air in the pipe A, in consequence of its elasticity, raises the valve S, and partially passes into the cylinder. The air being thus rarefied, water rises in the pipe until the pressure of the liquid column, together with the tension of the rarefied air which remains in the tube, counterbalances the pressure of the atmosphere on the water of the reservoir.

When the piston descends, the valve S closes by its own weight, and prevents the return of the air from the cylinder into the tube A. The air compressed by the piston opens the valve O, and escapes into the atmosphere by the pipe C. With a second stroke of the piston the same series of phenomena is produced, and after a few strokes the water reaches the cylinder. The effect is now somewhat modified; during the descent of the piston, the valve S closes, and the water raises the valve O, and passes above the piston, by which it is lifted into the upper reservoir D. There is now no more air in the pump, and the water, forced by the atmospheric pressure, rises with the piston, provided that when it is at the summit of its course it is not more than 34 feet above the level of the water in which the tube A dips, for we have seen (148) that a column of water of this height is equal to the pressure of the atmosphere.

In practice the height of the tube A does not often exceed 26 to 28 feet, for, although the atmospheric pressure can support a higher column, the vacuum produced in the barrel is not perfect, owing to the fact that the piston does not fit exactly on the bottom of the barrel. But when the water has passed the piston, it is the ascending force of the latter which raises it, and the height to which it can be brought depends on the force which moves the piston.

192. **Suction and force pump.**—The action of this pump, a model of which is represented in fig. 150, depends both on exhaustion and on pressure. At the base of the barrel, where it is connected with the tube A, there is a valve, S, which opens upwards. Another valve, O, opening in the same direction, closes the aperture of a conduit, which passes from a hole, *o*, near the valve S into a vessel, M, which is called the *air chamber*. From this chamber there is another tube, D, up which the water is forced.

At each ascent of the piston B, which is solid, the water rises through the tube A into the barrel. When the piston sinks, the valve S closes, and the water is forced through the valve O into the reservoir M, and from thence into the tube D. The height to which it can be raised in this tube depends solely on the motive force which works the pump.

If the tube D were a prolongation of the tube J*ao*, the flow would be intermittent; it would take place when the piston descended, and would cease as soon as it ascended. But between these tubes there is an in-

terval, which, by means of the air in the reservoir M, ensures a continuous flow. The water forced into the reservoir M divides into two parts, one of which, rising in D, presses on the water in the reservoir by its weight; while the other, in virtue of this pressure, rises in the reservoir above the

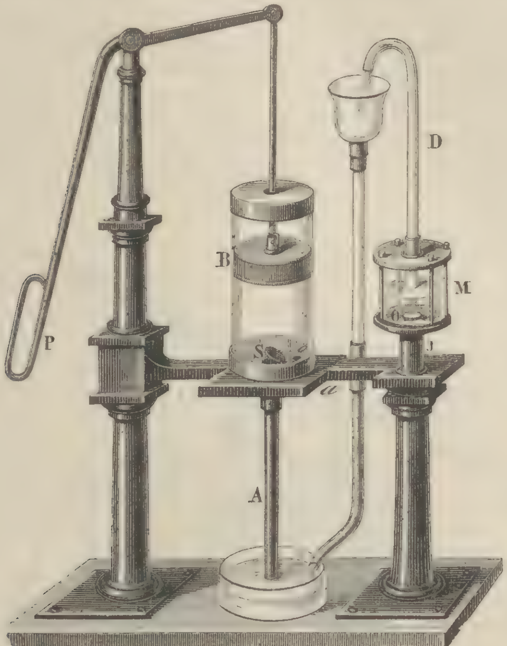


Fig. 150.

lower orifice of the tube D, compressing the air above. Consequently when the piston ascends, and no longer forces the water into M, the air of the reservoir, by the pressure it has received, reacts on the liquid, and raises it in the tube D, until the piston again descends, so that the jet is continuous.

193. **Load which the piston supports.**—In the suction pump, when once the water fills the pipe and the barrel as far as the spout, *the effort necessary to raise the piston is equal to the weight of a column of water, the base of which is this piston, and the height, the vertical distance of the spout from the level of the water in the reservoir, that is, the height to which the water is raised.* For if H is the atmospheric pressure, h the height of the water above the piston, and h' the height of the column which fills the suction tube A, and the lower part of the barrel, the pressure above the piston is obviously $H+h$, and that below is $H-h'$, since the weight of the column h' tends to counterbalance the atmospheric pressure. But the pressure $H-h'$ tending to raise the piston, the effec-

tive resistance is equal to the excess of $H+h$ over $H-h'$, that is to say, to $h+h'$, which is what was to be proved.

In the suction and force pump it is readily seen that the pressure which the piston supports is also equal to the weight of a column of water, the base of which is the section of the piston, and the height that to which the water is raised.

194. **Fire engine.**—The fire engine is a force pump in which a steady jet is obtained by the aid of an air chamber, and also by two pumps working alternately (fig. 151). The two pumps *m* and *n*, worked by the same lever PQ, are immersed in a tank, and which is kept filled with water as long as the pump works. From the arrangement of the valves it will be seen, that when one pump *n* draws water from the tank, the

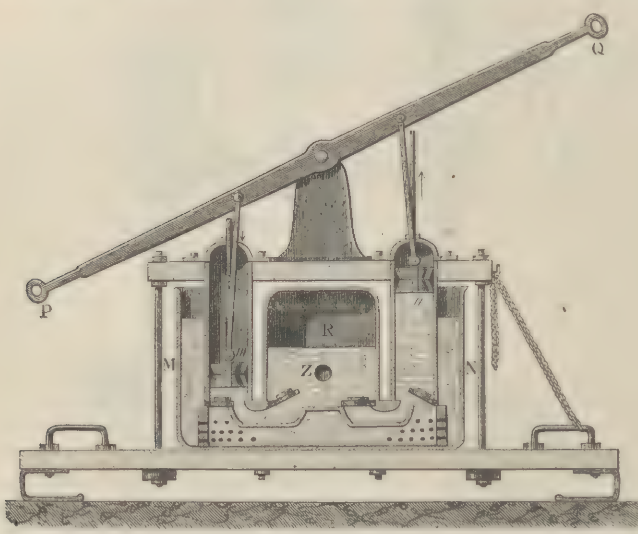


Fig. 151.

other *m* forces it into the *air chamber* R; whence, by an orifice Z, it passes into the delivery tube, by which it can be sent in any direction.

Without the air chamber the jet would be intermittent. For as the velocity of water on entering the reservoir is less than on emerging, the level of the water rises above the orifice Z, compressing the air which fills the reservoir. Hence, whenever the pistons stop, the air thus compressed reacting on the liquid forces it out during this momentary stoppage, and thus keep up a constant flow.

195. **Velocity of efflux. Torricelli's theorem.**—Let us imagine an aperture made in the bottom of any vessel, and consider the case of a particle of liquid on the surface, without reference to those which are beneath. If this particle fell freely, it would have a velocity on reaching

the orifice equal to that of any other body falling through the distance between the level of the liquid and the orifice. This, from the laws of falling bodies, is $\sqrt{2gh}$, in which g is the accelerating force of gravity, and h the height. If the liquid be maintained at the same level, for instance, by a stream of water running into the vessel sufficient to replace what has escaped, the particles will follow one another with the same velocity, and will issue in the form of a stream. Since pressure is transmitted equally in all directions, a liquid would issue from an orifice in the side with the same velocity, provided the depth were the same.

The law of the velocity of efflux was discovered by Torricelli. It may be enunciated as follows : *The velocity of efflux is the velocity which a freely falling body would have on reaching the orifice after having started from a state of rest at the surface.* It is algebraically expressed by the formula $v = \sqrt{2gh}$.

It follows directly from this law, that the velocity of efflux depends on the depth of the orifice below the surface, and not on the nature of the liquid. Through orifices of equal size and of the same depth, water and mercury would issue with the same velocity, for although the density of the latter liquid is greater, the weight of the column, and consequently the pressure, is greater too. It follows further that the velocities of efflux are directly proportional to the square roots of the depths of the orifices. Water would issue from an orifice 100 inches below the surface with ten times the velocity with which it would issue from one an inch below the surface.

The quantities of water which issue from orifices of different areas are very nearly proportional to the size of the orifice, provided the level remains constant.

196. **Direction of the jet from lateral orifices.**—From the principle of the equal transmission of pressure, water issues from an orifice in the side of a vessel with the same velocity as from an aperture in the bottom of a vessel at the same depth. Each particle of a jet issuing from the side of a vessel begins to move horizontally with the velocity above mentioned, but it is at once drawn downward by the force of gravity, in the same manner as a bullet fired from a gun, with its axis horizontal. It is well known that the bullet describes a parabola with a vertical axis, the vertex being the muzzle of the gun. Now since each particle of the jet moves in the same curve, the jet itself takes the parabolic form, as shown in fig. 152.

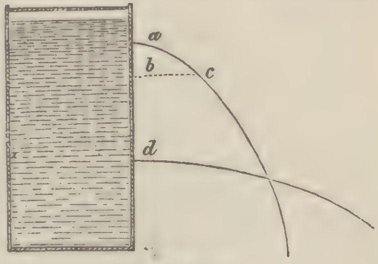


Fig. 152.

It may be remarked, that in every parabola there is a certain point called the focus, and that the distance from the vertex to the focus fixes the magnitude of a parabola in much the same manner as the distance from the centre to

the circumference fixes the magnitude of a circle. Now it is easily capable of proof that the focus is as much below as the surface of the water is above the orifice. Accordingly the jets formed by water coming from orifices at different depths below the surface, take different forms as shown in fig. 152.

197. **Height of the jet.**—If a jet issuing from an orifice in a vertical direction has the same velocity as a body would have which fell from the surface of the liquid to that orifice, the jet ought to rise to the level of the liquid. It does not, however, reach this; for the particles which fall hinder it. But by inclining the jet at a small angle with the vertical, it reaches about $\frac{9}{10}$ of the theoretical height, the difference being due to friction and to the resistance of the air. By experiments of this nature the truth of Torricelli's law has been demonstrated.

198. **Quantity of efflux. Vena contracta.**—If we suppose the sides of a vessel containing water to be thin, and the orifice to be a small circle whose area is A, we might think that the quantity of water E discharged per second would be given by the formula $A\sqrt{2gh}$, since each particle has, on the average, a velocity equal to $\sqrt{2gh}$, and particles issue from each point of the orifice. But this is by no means the case. This may be explained by reference to fig. 153, in which AB represents an orifice in the bottom of a vessel—what is true in this case being equally true of an orifice in the side of the vessel. Every particle above AB endeavours to pass out of the vessel, and in so doing exerts a pressure on those near it. Those that issue near A and B exert pressures in the directions MM and NN; those near the centre of the orifice in the direction RQ, those in the intermediate parts in the directions PQ, PQ. In consequence, the water within the space PQP is unable to escape, and that which does escape, instead of assuming a cylindrical form, at first contracts, and takes the form of a truncated cone. It is found that the escaping jet continues to contract, until at a distance from the orifice about equal to the diameter of the orifice. This part of the jet is called the *vena contracta*. It is found that the area of its smallest section is about $\frac{5}{8}$ or 0·62 of that of the orifice. Accordingly the true value of the efflux per second is given approximately by the formula

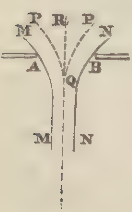


Fig. 153.

$$E = 0{\cdot}62A\sqrt{2gh}$$

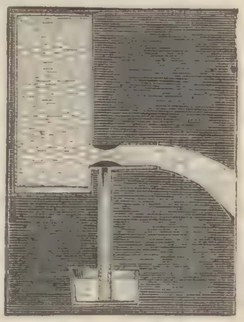
or the actual value of E is about 0·62 of its *theoretical amount*.

199. **Influence of tubes on the quantity of efflux.**—The result given in the last article has reference to an aperture in a thin wall. If a cylindrical or conical efflux-tube or *ajutage* is fitted to the aperture, the amount of the efflux is considerably increased, and in some cases falls but little short of its theoretical amount.

A short cylindrical ajutage, whose length is from two to three times its diameter, has been found to increase the efflux per second to about $0{\cdot}82A\sqrt{2gh}$. In this case, the water on entering the ajutage forms a contracted vein (fig. 155), just as it would do on issuing freely into the air;

but afterwards it expands, and, in consequence of the adhesion of the water to the interior surface of the tube, has, on leaving the ajutage, a section greater than that of the contracted vein. The contraction of the jet within the ajutage causes a partial vacuum. If an aperture is made in the ajutage, near the point of greatest contraction, and fitted with a vertical tube, the other end of which dips into water (fig. 154), it is found that water rises in the vertical tube, thereby proving the formation of a partial vacuum.

Fig. 154.



If the ajutage has the form of a conic frustrum whose larger end is at the aperture, if the dimensions are properly chosen, the efflux per second may be raised to $0{\cdot}92A\sqrt{2gh}$. If the smaller end of a frustrum of a cone of suitable dimensions be fitted to the orifice, the efflux may be still further increased, and fall very little short of the theoretical amount.

When the ajutage has more than a certain length, a considerable diminution takes place in the amount of the efflux; for example, if its length is 48 times its diameter, the efflux is reduced to $0{\cdot}63A\sqrt{2gh}$. This arises from the fact, that, when water passes along cylindrical tubes, the resistance increases with the length. This effect will be best understood by the following statement. If, in fig. 154, we suppose the ajutage to be replaced by a tube exceeding its diameter in length by a hundred times, at least, the efflux per second E_1 will be related to that from the ajutage E as given above in a manner approximately given by the formula $E_1 = E - 7{\cdot}376\sqrt{\frac{D}{L}}$, where D denotes the diameter of the tube and L its length: thus if the diameter were 1 inch, and the length 300 feet, the efflux per second E_1 would be about one-eighth part of E. This result is true of water at ordinary temperatures. The resistance which gives rise to this result is called *hydraulic friction*; it is independent of the material of the tube, provided it be not roughened; but depends in a considerable degree on the viscosity of the liquid; for instance, ice-cold water experiences a greater resistance than lukewarm water.

Fig. 155.

200. **Form of the jet.**—After the contracted vein, the jet has the form of a solid rod for a short distance, but then begins to separate into drops which present a peculiar appearance. They seem to form a series of ventral and nodal segments (fig. 156). The ventral segments consist of drops extended in a horizontal direction, and the nodal segments in a longitudinal direction. And as the ventral and nodal segments have respectively a fixed position, each drop must alternately become elongated and flattened while it is falling (fig. 157). Between any two drops there are smaller ones, so that the whole jet has a tube-like appearance.

If the aperture is not circular the form of the jet undergoes curious changes.

Fig. 156.

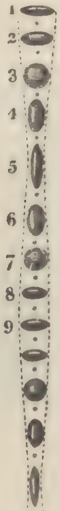


Fig. 157.

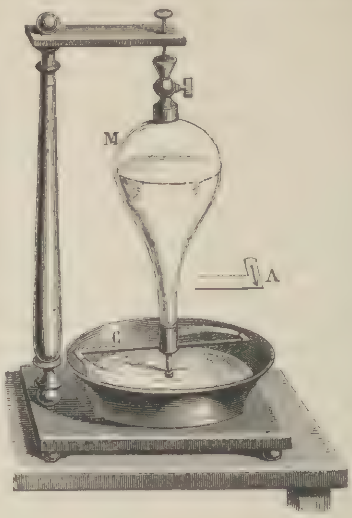


Fig. 158.

201. **Hydraulic tourniquet.**—If water be contained in a vessel, and an aperture made in one of the sides, the pressure at this point is removed, for it is expended in forcing out the water; but it remains on the other side; and if the vessel were movable in a horizontal direction, it would move in a direction opposite that of the issuing jet. This is illustrated by the apparatus known as the *hydraulic tourniquet*, or *Barker's mill* (fig. 158). It consists of a glass vessel, M, containing water, and capable of moving about its vertical axis. At the lower part there is a tube, C, bent horizontally in opposite directions at the two ends. If the vessel were full of water and the tubes closed, the pressures on the sides of C would balance each other, being equal and acting in contrary directions; but, being open, the water runs out, the pressure is not exerted on the open part, but only on the opposite side, as shown in the figure A. And this pressure, not being neutralised by an opposite pressure, imparts a rotatory motion in the direction of the arrow, the velocity of which increases with the height of the liquid and the size of the aperture.

The same principle may be illustrated by the following experiment. A tall cylinder containing water and provided with a lateral stopcock near the bottom is placed on a light shallow dish on water, so that it easily floats. On opening the stopcock so as to allow water to flow out, the vessel is observed to move in a direction diametrically opposite that in which the water is issuing.

Segner's water-wheel and the reaction machine depend on this prin-

ciple. Rotating fireworks also act on the same principle; that is, an unbalanced reaction from the heated gases which issue from openings in them gives them motion in the opposite direction.

202. **Water-wheels. Turbines.**—When water is continuously flowing from a higher to a lower level, it may be used as a motive power. This is effected by means of *water-wheels*; that is, wheels provided with buckets or float-boards at the circumference, and on which the water acts either by pressure or by impact.

Water-wheels turn in a vertical plane round a horizontal axis, and are of two principal kinds, *undershot* and *overshot*.

In *undershot* wheels the float-boards are at right angles to the circumference of the wheel. The lowest float-boards are immersed in the water, which flows with a velocity depending on the height of the fall. Such wheels are applicable where the quantity of water is great, but the fall inconsiderable.

Overshot wheels are used with a small quantity of water which has a high fall, as with small mountain streams. On the circumference of the wheel there are buckets of a peculiar shape. The water falls into the buckets on the upper part of the wheel, which is thus moved by the weight of the water, and as each bucket arrives at the lowest point of revolution it discharges all the water, and ascends empty.

The *turbine* is a horizontal water-wheel, and is similar in principle to the hydraulic tourniquet. But instead of the horizontal tubes there is a horizontal drum, containing curved vertical walls; the water, in issuing from the turbine, pressing against these walls, exerts a reaction, and turns the whole wheel about a vertical axis.

Turbines have the advantage of being of small bulk for their power, and equally efficient for the highest and the lowest falls.

In all prime movers worked by a fall of water, it is of the utmost importance to prevent the water from acting on the machine by impact, and thereby to prevent the great loss of power which is always occasioned by the impact of imperfectly elastic bodies.

203. **Mariotte's bottle, its use.**—Mariotte's bottle presents many curious effects of the pressure of the atmosphere, and furnishes a means of obtaining a constant flow of water. It consists of a large narrow-mouth bottle, in the neck of which there is a tightly-fitting cork (fig. 159). Through this a tube passes, open at both ends. In the sides of the bottle there are three tubulures, each with a narrow orifice, and which can be closed at will.

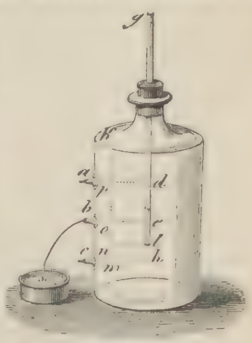


Fig. 159.

The bottle and the tube being quite filled with water, let us consider what will be the effect of opening successively one of the tubulures, *a*, *b*, and *c*, supposing, as represented in the figure, that the lower extremity of *g* is between the tubulures *b* and *c*.

i. If the tubulure *b* is open the water flows out, and the surface sinks

in the tube g until it is on the same level as b, when the flow stops. This flow arises from the excess of pressure at the point c over that at b. The pressure at c is the same as the pressure of the atmosphere. But when once the level is the same at b and at c, the efflux ceases, for the atmospheric pressure on all points of the same horizontal layer, bc, is the same (90).

ii. If now the tubulure b is closed, and a opened, no efflux takes place; on the contrary, air enters by the orifice a, and water ascends in the tube g, as high as the layer ad, and then equilibrium is established.

iii. If the orifices a and b are closed, and c opened, an efflux having constant velocity takes place, as long as the level of the water is not below the open end, l, of the tube. Air enters bubble by bubble at l, and takes the place of the water which has flowed out.

In order to show that the efflux at the orifice c is constant, it is necessary to demonstrate that the pressure on the horizontal layer ch is always equal to that of the atmosphere in addition to the pressure of the column hl. Now suppose that the level of the water has sunk to the layer ad. The air which has penetrated into the flask supports a pressure equal to that of the atmosphere diminished by that of the column of liquid pn, or $H - pn$. In virtue of its elasticity this pressure is transmitted to the layer ch. But this layer further supports the weight of a column of water, pm, so that the pressure at m is really $pm + H - pn$, or $H + mn$, that is to say, $H + hl$.

In the same manner it may be shown that this pressure is the same when the level sinks to b, and so on as long as the level is higher than the aperture l. The pressure on the layer ch is therefore constant, and consequently the velocity of the efflux. But when once the level is below the point l, the pressure decreases, and with it the velocity.

To obtain a constant flow by means of Mariotte's bottle, it is filled with water, and the orifice which is below the tube l is opened. The rapidity of the flow is proportional to the square root of the height hl.

BOOK V.

ACOUSTICS.

CHAPTER I.

PRODUCTION, PROPAGATION, AND REFLECTION OF SOUND.

204. **Object of acoustics.**—The study of sounds, and that of the vibrations of elastic bodies, form the object of *acoustics*.

Music considers sounds with reference to the pleasurable feelings they are calculated to excite. Acoustics is concerned with the questions of the production, transmission, and comparison of sounds. To which may be added the physiological question of the perception of sounds.

205. **Sound and noise.**—*Sound* is a peculiar sensation excited in the organ of hearing by the vibratory motion of bodies, when this motion is transmitted to the ear through an elastic medium.

All sounds are not identical; they present differences by which they may be distinguished, compared, and their relations determined.

Sounds are distinguished from *noises*. Sound properly so called, or *musical sound*, is that which produces a continuous sensation, and the musical value of which can be determined: while noise is either a sound of too short a duration to be determined, like the report of a cannon, or else it is a confused mixture of many discordant sounds, like the rolling of thunder or the noise of the waves. Nevertheless, the difference between sound and noise is by no means precise; Savart has shown that there are relations of height in the case of noise, as well as in that of sound; and there are said to be certain ears sufficiently well organised to determine the musical value of the sound produced by a carriage rolling on the pavement.

206. **Cause of sound.**—Sound is always the result of rapid oscillations imparted to the molecules of elastic bodies, when the state of equilibrium of these bodies has been disturbed either by a shock or friction. Such bodies tend to regain their first position of equilibrium, but only reach it after performing, on each side of that position, very rapid vibratory movements, the amplitude of which quickly decreases.

A body which produces a sound is called a *sonorous* body. As understood in England and Germany, a vibration comprises a motion to *and* fro; in France, on the contrary, a vibration means a movement to *or* fro. The French vibrations are with us semi-vibrations, an *oscillation* or *vi-*

bration is the movement of the vibrating molecule in only one direction; a *double* or *complete vibration* comprises the oscillation both backwards and forwards. Vibrations are very readily observed. If a light powder is sprinkled on a body which is in the act of yielding a musical sound, a bell jar held horizontally in the hand, for example, a rapid motion is imparted to the powder which renders visible the vibrations of the body; and in the same manner, if a stretched cord be smartly pulled and let go its vibrations are apparent to the eye.

207. **Sound is not propagated in vacuo.**—The vibrations of elastic bodies can only produce the sensation of sound in us by the intervention of a medium interposed between the ear and the sonorous body, and vibrating with it. This medium is usually the air, but all gases, vapours, liquids, and solids also transmit sounds.

The following experiment shows that the presence of a ponderable medium is necessary for the propagation of sound. A small metallic bell, which is continually struck by a small hammer, by means of clockwork, or an ordinary musical box, is placed under the receiver of the air-pump (fig. 160). As long as the receiver is full of air at the ordinary pressure, the sound is transmitted, but in proportion as the air is exhausted the sound becomes feebler, and is imperceptible in a vacuum.

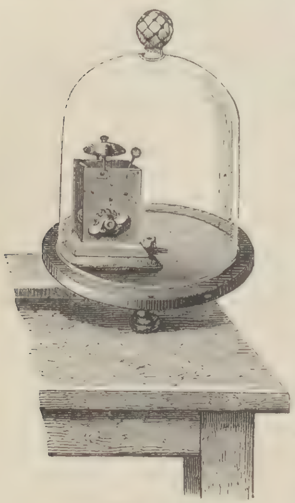


Fig. 160.

To ensure the success of the experiment, the bellwork or musical box must be placed on wadding; for otherwise the vibrations would be transmitted to the air through the plate of the machine.

208. **Sound is propagated in all elastic bodies.**—If, in the above experiment, after the vacuum has been made, any vapour or gas be admitted, the sound of the bell will be heard, showing that sound is propagated in this medium as in air.

Sound is also propagated in liquids. When two bodies strike against each other under water, the shock is distinctly heard. And a diver at the bottom of the water can hear the sound of voices on the bank.

The conductibility of solids is such, that the scratching of a pen at the end of a piece of wood is heard at the other end. The earth conducts sound so well, that at night, when the ear is applied to the ground, the steps of horses or any other noise at great distances is heard.

209. **Propagation of sound in the air.**—In order to simplify the theory of the propagation of sound in the air, we shall first consider the case in which it is propagated in a cylindrical tube of indefinite length. Let MN, fig. 161, be a tube filled with air at a constant pressure and

temperature, and let P be a piston oscillating rapidly from A to *a*. When the piston passes from A to *a* it compresses the air in the tube. But in consequence of the great compressibility, the condensation of the air does

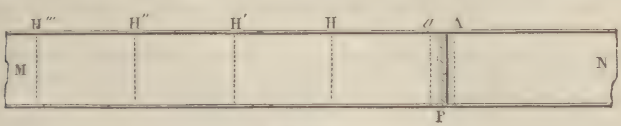


Fig. 161.

not take place at once throughout the whole length of the tube, but solely within a certain length, *a*H, which is called the *condensed wave.*

If the tube MN be supposed to be divided into lengths equal to *a*H, and each of these lengths divided into layers parallel to the piston, it may be shown by calculation, that when the first layer of the wave *a*H comes to rest, the motion is communicated to the first layer of the second wave HH′, and so on from layer to layer in all parts of H′H″, H″H‴. The condensed wave advances in the tube, each of its parts having successively the same degrees of velocity and condensation.

When the piston returns in the direction *a*A, a vacuum is produced behind it, which causes an expansion of the air in contact with its posterior face. The next layer expanding in turn brings the first to its original state of condensation, and so on from layer to layer. Thus, when the piston has returned to A, an *expanded wave* is produced of the same length as the condensed wave, and directly following it in the tube where they are propagated together, the corresponding layers of the two waves possessing equal and contrary velocities.

The whole of a condensed and expanded wave forms an *undulation;* that is, an undulation comprehends that part of the column of air affected during the backward and forward motion of the piston. The *length of an undulation* is the space which sound traverses during a complete vibration of the body which produces it. This length is less in proportion as the vibrations are more rapid.

It is important to remark that if we consider a single row of particles, which when at rest occupy a line parallel to the axis of the cylinder, for instance, those along AH″ (fig. 161), we shall find they will have respectively at the same instant all the various velocities which the piston has had successively while oscillating from A to *a* and back to A. So that if in fig. 26 AH′ represents the length of one undulation, the curved line H′PQA will represent the various velocities which all the points in the line AH′ have *simultaneously*: for instance, at the instant the piston has returned to A, the particle at M will be moving to the right with a velocity represented by QM, the particle at N will be moving to the left with a velocity represented by PN, and so on of the other particles.

When an undulatory motion is transmitted through a medium, the motions of any two particles are said to be in the same *phase* when those particles move with equal velocities in the same direction; the motions are said to be in opposite phases when the particles move with the same

velocities in opposite directions. It is plain, from an inspection of fig. 26, that when any two particles are separated by a distance equal to half an undulation, their motions are always in opposite phases, but if their distance equals the length of an undulation their motions are in the same phase.

A little consideration will show that in the *condensed wave* the condensation will be greatest at the middle of the wave, and likewise that the *expanded wave* will be most rarefied at its middle.

It is an easy transition from the theory of the motion of sonorous waves in a cylinder to that of their motions in an uninclosed medium. It is simply necessary to apply, in all directions, to each molecule of the vibrating body, what has been said about a piston moveable in a tube. A series of spherical waves alternately condensed and rarefied is produced around each centre of disturbance. As these waves are contained within two concentrical spherical surfaces, whose radii gradually increase while the length of the undulation remains the same, their mass increases with the distance from the centre of disturbance, so that the amplitude of the vibration of the molecules gradually lessens, and the intensity of the sound diminishes.

It is these spherical waves, alternately condensed and expanded, which in being propagated transmit sound. If many points are disturbed at the same time, a system of waves is produced around each point. But all these waves are transmitted one through the other without modifying either their lengths or their velocities. Sometimes condensed or expanded waves coincide with others of the same nature to produce an effect equal to their sum; sometimes they meet and produce an effect equal to their difference. If the surface of still water be disturbed at two or more points, the co-existence of waves becomes sensible to the eye.

210. **Causes which influence the intensity of sound.**—Many causes modify the force or the *intensity* of the sound. These are, the distance of the sonorous body, the amplitude of the vibrations, the density of the air at the place where the sound is produced, the direction of the currents of air, and lastly, the proximity of other sonorous bodies.

i. *The intensity of sound is inversely as the square of the distance of the sonorous body from the ear.* This law has been deduced by calculation, but it may be also demonstrated experimentally. Let us suppose several sounds of equal intensity—for instance, bells of the same kind, struck by hammers of the same weight, falling from equal heights. If four of these bells are placed at a distance of 20 yards from the ear, and one at a distance of 10 yards, it is found that the single bell produces a sound of the same intensity as the four bells struck simultaneously. Consequently, for double the distance the intensity of the sound is only one fourth.

The distance at which sounds can be heard depends on their intensity. The report of a volcano at St. Vincent was heard at Demerara, 300 miles off, and the firing at Waterloo was heard at Dover.

ii. *The intensity of the sound increases with the amplitude of the vibrations of the sonorous body.* The connection between the intensity of the sound and the amplitude of the vibrations is readily observed by means of

vibrating cords. For if the cords are somewhat long, the oscillations are perceptible to the eye, and it is seen that the sound is feebler in proportion as the amplitude of the oscillations decreases.

iii. *The intensity of sound depends on the density of the air in the place in which it is produced.* As we have already seen (199), when an alarum moved by clockwork is placed under the bell-jar of the air pump, the sound becomes weaker in proportion as the air is rarefied.

In hydrogen, which is about $\frac{1}{14}$ the density of air, sounds are much feebler, although the pressure is the same. In carbonic acid, on the contrary, whose density is 1·529, sounds are more intense. On high mountains, where the air is much rarefied, it is necessary to speak with some effort in order to be heard, and the discharge of a gun produces only a feeble sound.

The ticking of a watch is heard in water at a distance of 23 feet, in oil of 16½ in alcohol of 13, and in air of only 10 feet.

iv. *The intensity of sound is modified by the motion of the atmosphere and the direction of the wind.* In calm weather sound is always better propagated than when there is wind; in the latter case, for an equal distance, sound is more intense in the direction of the wind than in the contrary direction.

v. Lastly, *sound is strengthened by the proximity of a sonorous body.* A string made to vibrate in free air and not near a sounding body has but a very feeble sound; but when it vibrates above a sounding-box, as in the case of the violin, guitar, or violoncello, its sound is much more intense. This arises from the fact that the box and the air which it contains vibrate in unison with the string. Hence the use of sounding-boxes in stringed instruments.

Fig. 162.

211. **Apparatus to strengthen sound.**—The apparatus represented in fig. 162 was used by Savart to show the influence of boxes in strengthening

sound. It consists of a hemispherical brass vessel, A, which is set in vibration by means of a strong bow. Near it there is a hollow cardboard cylinder, B, closed at the further end. By means of a handle this cylinder can be turned on its support, so as to be inclined at any given degree towards the vessel. The cylinder is fixed on a slide, C, by which means it can be placed at any distance from A. When the vessel is made to vibrate, the strengthening of the sound is very remarkable. But the sound loses almost all its intensity if the cylinder is turned away, and it becomes gradually weaker when the cylinder is removed to a greater distance, showing that the strengthening is due to the vibration of the air in the cylinder.

The cylinder B is made to vibrate in unison with the brass vessel by adjusting it to a certain depth, which is effected by making one part slide into the other.

Vitruvius states that in the theatres of the ancients resonant brass vessels were placed to strengthen the voices of the actors.

212. **Influence of tubes on the transmission of sound.**—The law that the intensity of sound decreases in inverse proportion to the square of the distance does not apply to the case of tubes, especially if they are straight and cylindrical. The sonorous waves in that case are not propagated in the form of increasing concentrical spheres, and sound can be transmitted to a great distance without any perceptible alteration. M. Biot found that in one of the Paris water pipes, 1040 yards long, the voice lost so little of its intensity, that a conversation could be kept up at the ends of the tube in a very low tone. The weakening of sound becomes, however, perceptible in tubes of large diameter, or where the sides are rough. This property of transmitting sounds was first used in England for *speaking tubes.* They consist of caoutchouc tubes of small diameter passing from one room to another. If a person speaks at one end of the tube, he is distinctly heard by a person with his ear at the other end.

From M. Biot's experiments it is evident that a communication might be made between two towns by means of speaking tubes. The velocity of sound is 1125 feet in a second at 16·6 C., so that a distance of 50 miles would be traversed in four minutes.

213. **Velocity of sound in gases.**—Since the propagation of sonorous waves is gradual, sound requires a certain time for its transmission from one place to another, as is seen in numerous phenomena. For example the sound of thunder is only heard some time after the flash of lightning has been seen, although both the sound and the light are produced simultaneously ; and in like manner we see a mason in the act of striking a stone before hearing the sound.

The velocity of sound in air has often been the subject of experimental determination.

The most accurate of the direct meausurements was made by Moll and Van Beck in 1823. Two hills near Amsterdam, Kooltjesberg and Zevenboomen, were chosen as stations ; their distance from each other as determined trigonometrically was 57,971 feet, or nearly eleven miles. Cannon were fired at stated intervals simultaneously at each station, and

the time which elapsed between seeing the flash and hearing the sound was noted by chronometers. This time could be taken as that which the sound required to travel between the two stations; for it will be subsequently seen that light takes an inappreciable time to travel between the above distance. Introducing corrections for the barometric pressure, temperature and hygrometric state, and eliminating the influence of the wind, Moll and Van Beck's results as recalculated by Schröder van der Kolk give 1092·78 feet as the velocity of sound in one second in dry air and under a pressure of 760 mm.

The velocity of sound increases with the increase of temperature; it may be calculated for any temperature $t°$ from the formula,

$$v = 1093\sqrt{1 + 0{\cdot}003665t}$$

where 1093 is the velocity at 0° C., and 0·003665 the coefficient of expansion for 1° C. This amounts to an increase of nearly two feet for every degree centigrade. For the same temperature it is independent of the density of the air, and consequently of the pressure. It is the same for the same temperature with all sounds, whether they be strong or weak, deep or acute. M. Biot found, in his experiments on the conductivity of sound in tubes, that when a well-known air was played on a flute at one end of a tube 1040 yards long, it was heard without alteration at the other end, from which he concluded that the velocity of different sounds is the same. For the same reason the tune played by a band is heard at a great distance without alteration, except in intensity, which could not be the case if some sounds travelled more rapidly than others.

This cannot, however, be admitted as universally true. Earnshaw, by a profound mathematical investigation of the laws of the propagation of sound, has found that the velocity of a sound depends on its strength; and, accordingly, that a violent sound ought to be propagated with greater velocity than a gentler one. This conclusion is confirmed by an observation made by Captain Parry on his Arctic expedition. During artillery practice it was found, by persons stationed at a considerable distance from the guns, that the report of the cannon was heard before the command of fire given by the officer. And more recently, Mallet made a series of experiments on the velocity with which sound is propagated in rocks, by observing the times which elapsed before blastings made at Holyhead were heard at a distance. He found that the larger the charge of gunpowder, and therefore the louder the report, the more rapid was the transmission. With a charge of 2000 pounds of gunpowder the velocity was 967 feet in a second, while with a charge of 12,000 it was 1210 feet in the same time.

MM. Bravais and Martins found in 1844, that sound travelled with the same velocity from the base to the summit of the Faulhorn as from the summit to the base.

Mallet has investigated the velocity of the transmission of sound in various rocks, and finds that it is as follows:

Wet sand	825 ft. in a second.
Contorted, stratified quartz and slate rock .	1088 „

Discontinuous granite	1306 ft. in a second.
Solid granite	1664 „

The velocity of sound varies in different gases. Dulong caused organ pipes to sound by means of different gases, and found that the velocity of sound at zero was as follows:

Carbonic acid	856 ft. in a second.
Oxygen	1040 „
Air	1093 „
Carbonic oxide	1106 „
Hydrogen	4163 „

214. **Formulæ for calculating the velocity of sound in gases.**—For calculating the velocity of sound in gases Newton gave a rule equivalent to the formula

$$v=\sqrt{\frac{e}{d}}$$

in which v represents the velocity of the sound or the distance it travels in a second, e the elasticity of the gas, and d its density.

This formula expresses that the velocity of the propagation of sound in gases *is directly as the square root of the elasticity of the gas, and inversely as the square root of its density*. It follows that the velocity of sound is the same under any pressure, for although the elasticity increases with greater pressure, the density increases in the same ratio. At Quito, where the mean pressure is only 21·8 inches, the velocity is the same as at the sea level, provided the temperature is the same.

If g be the force of gravity, h the barometric height reduced to the temperature zero, and δ the density of mercury, also at zero, it is clear that for a gas under the atmospheric pressure, $e=gh\delta$; and for zero Newton's formula becomes

$$v=\sqrt{\frac{gh\delta}{d}}$$

Now if we suppose the temperature of a gas to increase from 0° to t° its volume will increase from unity at zero to $1+\alpha t$ at t, α being the coefficient of expansion of the gas. But the density varies inversely as the volume, therefore d becomes $d\div(1+\alpha t)$. Hence

$$v=\sqrt{\frac{gh\delta}{d}(1+\alpha t)}$$

The values of v, obtained by this formula, are less than the experimental results. Laplace assigned as a reason for this discrepancy the heat produced by pressure in the condensed waves; and, by considerations based on this idea, Poisson and Biot have found that Newton's formula ought to be written $v=\sqrt{\frac{gh\delta}{d}(1+\alpha t)\frac{c}{c'}}$; c being the specific heat of the gas for a constant pressure, and c' its specific heat for a constant volume

(see Book VI.). When thus modified the results calculated by the formula agree with the experimental results.

The physical reason for introducing the constant $\frac{c}{c'}$ into the equation for the velocity of sound may be understood from the following considerations. We have already seen that sound is propagated in air by a series of alternate condensations and rarefactions of the layers. At each condensation heat is evolved, and this heat increases the elasticity, and thus the rapidity, with which each condensed layer acts on the next ; but, in the rarefaction of each layer, the same amount of heat disappears as was developed by the condensation, and its elasticity is diminished by the cooling. The effect of this diminished elasticity of the cooled layer is the same as if the elasticity of an adjacent wave had been increased, and the rapidity with which this latter would expand upon the dilated wave would be greater. Thus, while the average temperature of the air is unaltered, both the heating which increases the elasticity and the chilling which diminishes it concur in increasing velocity.

Knowing the velocity of sound, we can calculate approximately the distance at which it is produced. Light travels with such velocity that the flash or the smoke accompanying the report of a gun may be considered to be seen simultaneously with the explosion. Counting then the number of seconds which elapse between seeing the flash and hearing the sound, and multiplying this number by 1125, we get the distance in feet at which the gun is discharged. In the same way the distance of thunder may be estimated.

When a sounding body approaches the ear, the tone perceived is somewhat higher than the true one ; but if the source of sound recedes from the ear, the tone perceived is lower. The truth of this, which is known as *Doppler's principle*, will be apparent from the following considerations :—For when the source of sound and the ear are at rest, the air perceives n waves in a second ; but if the ear approaches the sound (or *vice versa*) it perceives more ; just as a ship meets more waves when it ploughs through them than if it is at rest. Conversely the ear receives a smaller number when it recedes from the source of sound. The effect in the first case is as if the sounding body emitted more vibrations in a second than it really does, and in the second case fewer. Hence in the first case the note appears higher ; in the second case lower.

If the distance which the ear traverses in a second towards the source of sound (supposed stationary) is s feet and the wave length of the particular tone is λ feet, then there are $\frac{s}{\lambda}$ waves in a second ; or also $\frac{ns}{c}$ for $\lambda = \frac{c}{n}$, where c is the velocity of sound (213). Hence the ear receives not only the n original waves but also $\frac{ns}{c}$ in addition. Therefore the number of vibrations which the ear actually perceives is

$$n' = n + \frac{ns}{c} = n\left(1 + \frac{s}{c}\right)$$

for an ear which approaches a tone; and by similar reasoning it is

$$n' = n - \frac{ns}{c} = n\left(1 - \frac{s}{c}\right)$$

for an ear receding from a tone.

To test Doppler's theory Buys Ballot stationed trumpeters on the Utrecht Railway, and also upon locomotives, and had the height of the approaching or receding tones compared with stationary ones by musicians. He thus found both the principle and the formula fully confirmed.

215. **Velocity of sound in liquids and in solids.**—The velocity of sound in water was investigated in 1827 by Colladon and Sturm. They moored two boats at a known distance in the Lake of Geneva. The first supported a bell immersed in water, and a bent lever provided at one end with a hammer which struck the bell, and at the other with a lighted wick, so arranged that it ignited some powder the moment the hammer struck the bell. To the second boat was affixed an ear-trumpet, the bell of which was in water, while the mouth was applied to the ear of the observer, so that he could measure the time between the flash of light and the arrival of sound by the water. By this method the velocity was found to be 4,708 feet in a second at the temperature 8·1°, or four times as great as in air.

The velocity of sound, which is different in different liquids, can be calculated by a formula analogous to that given above (214) as applicable to gases. In this way are obtained the number given in the following table. As in the case of gases, the velocity varies with the temperature, which is therefore appended in each case:

River water (Seine) . . .	13°C.	= 4714	ft. in a second.
" " "	30	= 5013	"
Artificial sea-water . . .	20	= 4761	"
Solution of common salt . .	18	= 5132	"
" " chloride of calcium .	23	= 6493	"
Absolute alcohol	23	= 3804	"
Turpentine	24	= 3976	"
Ether		= 3801	"

As a general rule, this elasticity of solids, as compared with the density, is greater than that of liquids, and consequently the propagation of sound is more rapid.

The difference is well seen in an experiment by M. Biot, who found that when a bell was struck by a hammer, at one end of an iron tube 3,120 feet long, two sounds were distinctly heard at the other end. The first of these was transmitted by the tube itself with a velocity x; and the second by the enclosed air with a known velocity a. The interval between the sounds was 2·5 seconds. The value of x obtained from the equation

$$\frac{3120}{a} - \frac{3120}{x} = 2{\cdot}5$$

shows that the velocity of sound in the tube is between 9 and 10 times as great as that in air.

To this class of phenomena belongs the fact that if the ear is held against a rock in which a blasting is being made at a distance, two distinct reports are heard, one transmitted through the rock to the ear, and the other transmitted through the air.

The velocity of sound in other solids has also been determined theoretically by Wertheim, by means of their coefficient of elasticity.

The following table gives the velocity, expressed in feet per second :—

Lead	4030	Pine	10900
Gold	5717	Oak	12622
Silver	8553	Ash	13314
Copper	11666	Elm	13516
Steel wire . . .	15470	Fir	15218
Iron	16822	Aspen	16677

The velocity in the direction of the fibres was greater than across them.

216. **Reflection of sound.**—So long as sonorous waves are not obstructed in their motion, they are propagated in the form of concentric spheres ; but, when they meet with an obstacle, they follow the general law of elastic bodies ; that is, they return upon themselves, forming new concentric waves, which seem to emanate from a second centre on the other side of the obstacle. This phenomenon constitutes the reflection of sound.

Fig. 163 represents a series of incident waves reflected from an obstacle, PQ. Taking, for example, the incident wave MCDN, emitted from

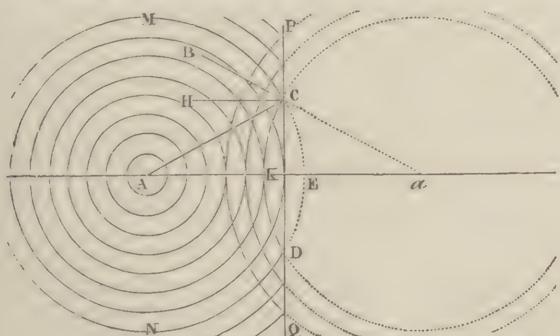


Fig. 163.

the centre A, the corresponding reflected wave is represented by the arc, CKD, of a circle, whose centre *a* is as far beyond the obstacle PQ as A is before it.

If any point, C, of the reflecting surface be joined to the sonorous centre, and if the perpendicular CH be let fall on the surface of this body, the angle ACH is called the *angle of incidence*, and the angle BCH, formed by the prolongation of *a*C, is the *angle of reflection.*

The reflection of sound is subject to the two following laws :

I. *The angle of reflection is equal to the angle of incidence.*

II. *The incident sonorous ray and the reflected ray are in the same plane perpendicular to the reflecting surface.*

From these laws it follows that the wave which is in the figure is propagated in the direction AC, takes the direction CB after reflection, so that an observer placed at B hears, besides the sound proceeding from the point A, a second sound, which appears to come from C.

The laws of the reflection of sound are the same as those for light and radiant heat, and may be demonstrated by similar experiments. One of the simplest of these is made with conjugate mirrors (see chapter on Radiant Heat): if in the focus of one of these mirrors a watch is placed, the ear placed in the focus of the second mirror hears the ticking very distinctly, even when the mirrors are at a distance of 12 or 13 yards.

217. **Echoes and resonances.**—An *echo* is the repetition of a sound in the air, caused by its reflection from some obstacle.

A very sharp quick sound can produce an echo when the reflecting surface is 55 feet distant, but for articulate sounds at least double that distance is necessary, for it may be easily shown that no one can pronounce or hear distinctly more than five syllables in a second. Now, as the velocity of sound at ordinary temperatures may be taken at 1125 feet in a second, in a fifth of that time sound would travel 225 feet. If the reflecting surface is 112.5 feet distant in going and returning, sound would travel through 225 feet. The time which elapses between the articulated and the reflected sound would, therefore, be a fifth of a second, the two sounds would not interfere, and the reflected sound would be distinctly heard. A person speaking with a loud voice in front of a reflector, at a distance of 112·5 feet, can only distinguish the last reflected syllable : such an echo is said to be *monosyllabic*. If the reflector were at a distance of two or three times 112·5 feet the echo would be *dissyllabic*, *trisyllabic*, and so on.

When the distance of the reflecting surface is less than 112·5 feet, the direct and the reflected sound are confounded. They cannot be heard separately, but the sound is strengthened. This is what is called *resonance*, and is often observed in large rooms. Bare walls are very resonant : but tapestry and hangings, which are bad reflectors, deaden the sound.

Multiple echoes are those which repeat the same sound several times : this is the case when two opposite surfaces (for example, two parallel walls) successively reflect sound. There are echoes which repeat the same sound 20 or 30 times. An echo in the château of Simonetta, in Italy, repeats a sound 30 times. At Woodstock there is one which repeats from 17 to 20 syllables.

As the laws of the reflection of sound are the same as those of light and heat, curved surfaces produce *acoustic foci* like the luminous and calorific foci produced by concave reflectors. If a person standing under the arch of a bridge speaks with his face turned towards one of the piers, the sound is reproduced near the other pier with such distinctness that

a conversation can be kept up in a low tone, which is not heard by any one standing in the intermediate spaces.

There is a square room with an elliptical ceiling, on the ground floor of the Conservatoire des Arts et Métiers, in Paris, which presents this phenomenon in a remarkable degree when persons stand in the two foci of the ellipse.

It is not merely by solid surfaces, such as walls, rocks, etc., that sound is reflected. It is also reflected by clouds, and on passing into a layer of air of greater density than its own; it is also further reflected by the vesicles of mist. When the weather is foggy, sounds undergo innumerable partial reflections, and are rapidly destroyed.

Whispering galleries are formed of smooth walls having a continuous curved form. The mouth of the speaker is presented at one point, and the ear of the hearer at another and distant point. In this case, the sound is successively reflected from one point to the other until it reaches the ear.

Different parts of the earth's surface are unequally heated by the sun, owing to the shadows of trees, evaporation of water, and other causes, so that in the atmosphere there are numerous ascending and descending currents of air of different density. Whenever a sonorous wave passes from a medium of one density into another it undergoes partial reflection, which, though not strong enough to form an echo, distinctly weakens the direct sound. This is doubtless the reason, as Humboldt remarks, why sound travels further at night than at daytime; even in the South American forests, where the animals, which are silent by day, fill the atmosphere in the night with thousands of confused sounds.

218. **Refraction of sound.** –It will be shown in the sequel that *refraction* is the change of direction which light and heat experience on passing from one medium to another. Sondhauss has found that sonorous waves are refracted like light and heat. He constructed gas lenses, by filling spherical or lenticular collodion envelopes with carbonic acid. With envelopes of paper or of goldbeater's skin the refraction of sound is not perceptible.

Sondhauss cut equal segments out of a large collodion balloon, and fastened them on the two sides of a sheet iron ring a foot in diameter, so as to form a hollow biconvex lens about 4 inches thick in the centre. This was filled with carbonic acid, and a watch was placed in the direction of the axis: the point was then sought, on the other side of the lens, at which the sound was most distinctly heard. It was found that when the ear was removed from the axis, the sound was scarcely perceptible; but that at a certain point on the axial line it was very distinctly heard. Consequently the sonorous waves in passing from the lens had converged towards the axis, their direction had been changed; in other words, they had been refracted.

The refraction of sound may be easily demonstrated by means of one of the very thin india-rubber balloons used as children's toys, inflated by carbonic acid. If the balloon be filled with hydrogen, no focus is detected;

it acts like a convex lens, and the divergence of the rays is increased, instead of their being converged to the ear.

219. **Speaking trumpet. Ear trumpet.**—These instruments are based both on the reflection of sound and on its conductibility in tubes.

The *speaking trumpet*, as its name implies, is used to render the voice audible at great distances. It consists of a slightly conical tin or brass

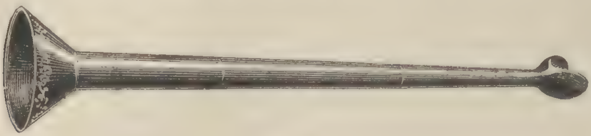


Fig. 164.

tube (fig. 164), very much wider at one end (which is called the *bell*), and provided with a mouthpiece at the other. The larger the dimensions of this instrument the greater is the distance at which the voice is heard. Its action is usually ascribed to the successive reflections of sonorous waves from the sides of the tube, by which the waves tend more and more to pass in a direction parallel to the axis of the instrument. It has, however, been objected to this explanation, that the sounds emitted by the speaking trumpet are not stronger solely in the direction of the axis, but in all directions, that the bell would not tend to produce parallelism in the sonorous wave, whereas it certainly exerts considerable influence in strengthening the sound. No satisfactory explanation has been given of the effect of the bell.

The *ear trumpet* is used by persons who are hard of hearing. It is essentially an inverted speaking trumpet, and consists of a conical metallic tube, one of whose extremities, terminating in a *bell*, receives the sound, while the other end is introduced into the ear. This instrument is the reverse of the speaking trumpet. The bell serves as a mouthpiece; that is, it receives the sounds coming from the mouth of the person who speaks. These sounds are transmitted by a series of reflections to the interior of the trumpet, so that the waves, which would become greatly developed, are concentrated on the auditory apparatus, and produce a far greater effect than divergent waves would have done.

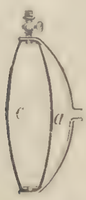


Fig. 165.

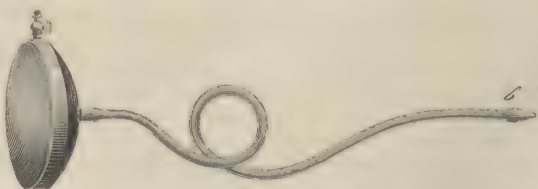


Fig. 166.

220. **Stethoscope.**—One of the most useful applications of acoustical principles is the stethoscope. Figs. 165, 166 represent an improved form

of this instrument devised by König. Two sheets of caoutchouc, *c* and *a*, are fixed to the circular edge of a hollow metal hemisphere; the edge is provided with a stopcock, so that the plates can be inflated, and then present the appearance of a double convex lens as represented in section in fig. 165. To a tubulure on the hemisphere is fixed a caoutchouc tube terminated by horn or ivory, *o*, which is placed in the ear (fig. 166).

When the membrane of the stethoscope is applied to the chest of a sick person, the beating of the heart and the sounds of respiration are transmitted to the air in the chamber CA, and from thence to the ear by means of the flexible tube. If several tubes are fixed to the instrument, as many observers may simultaneously auscultate the same patient.

CHAPTER II.

MEASUREMENT OF THE NUMBER OF VIBRATIONS.

221. **Savart's apparatus.**—*Savart's toothed wheel*, so called from the name of its inventor, is an apparatus by which the absolute number of vibrations corresponding to a given note can be determined. It consists of a solid oak frame in which there are two wheels, A and B (fig. 167); the larger wheel, A, is connected with the toothed wheel by means of a strap and a multiplying wheel, thereby causing the toothed wheel to revolve with great velocity; a card, E, is fixed on the frame, and, in revolving, the toothed wheel strikes against it, and causes it to vibrate. The card being struck by each tooth, makes as many vibrations as there are teeth. At the side of the apparatus there is an indicator, H, which gives the number of revolutions of the wheel, and consequently the number of vibrations in a given time.

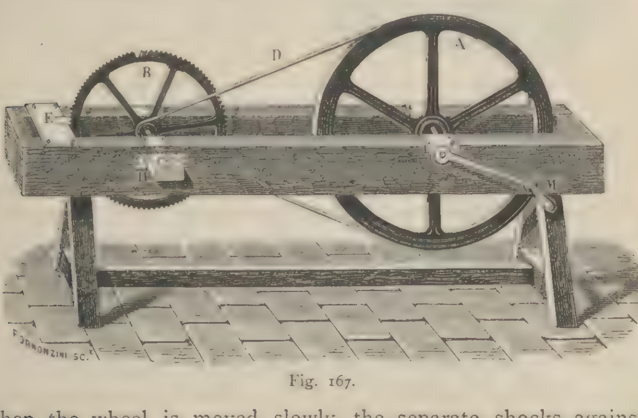


Fig. 167.

When the wheel is moved slowly, the separate shocks against the card are distinctly heard; but, if the velocity is gradually increased, the

sound becomes higher and higher. Having obtained the sound whose number of vibrations is to be determined, the revolution of the wheel is continued with the same velocity for a certain number of seconds. The number of turns of the toothed wheel B is then read off on the indicator, and this multiplied by the number of teeth in the wheel gives the total number of vibrations. Dividing this by the corresponding number of seconds, the quotient gives the number of vibrations per second for the given sound.

222. **Syren.**—The *syren* is an apparatus which, like Savart's wheel, is used to measure the number of vibrations of a body in a given time. The name 'syren' was given to it by its inventor, Cagniard Latour, because it yields sound under water.

It is made entirely of brass. Fig. 168 represents it fixed on the table of a bellows, by which a continuous current of air can be sent through it.

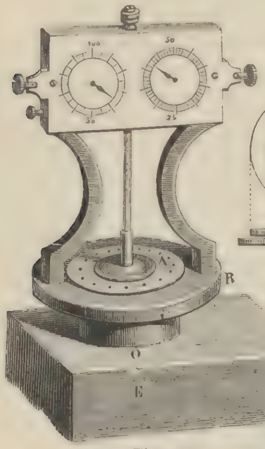
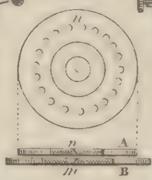


Fig. 168.

Fig. 170.



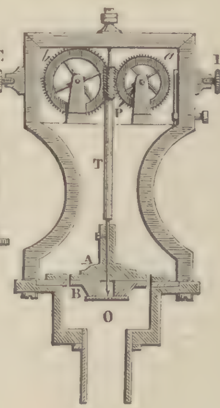


Fig. 169.

Figs. 169 and 170 show the internal details. The lower part consists of a cylindrical box, O, closed by a fixed plate, B. On this plate a vertical rod, T, rests, to which is fixed a disc, A, moving with the rod. In the plate B there are equidistant circular holes, and in the disc A are an equal number of holes of the same size, and the same distance from the centre as those of the plate. These holes are not perpendicular to the disc ; they are all inclined to the same extent in the same direction in the plate, and are inclined to the same extent in the opposite direction in the disc, so that when they are opposite each other they have the appearance represented in *mn*, fig. 170. Consequently, when a current of air from the bellows reaches the hole *m*, it strikes obliquely against the sides of the hole *n*, and imparts to the disc A a rotatory motion in the direction *n*A.

For the sake of simplicity, let us first suppose that in the movable disc A there are eighteen holes, and in the fixed plate B only one, which faces one of the upper holes. The wind from the bellows striking against the sides of the latter, the movable disc begins to rotate, and the space between two of its consecutive holes closes the hole in the lower plate. But as the disc continues to turn from its acquired velocity two holes are again opposite each other, a new impulse is produced, and so on. During a complete revolution of the disc the lower hole is eighteen times open and eighteen times closed. A series of effluxes and stoppages is thus produced, which makes the air vibrate, and ultimately produces a sound when the successive impulses are sufficiently rapid. If the fixed plate, like the moving disc, has eighteen holes, each hole would separately produce the same effect as a separate one, the sound would be eighteen times as intense, but the number of vibrations would not be increased.

In order to know the number of vibrations corresponding to the sound produced, it is necessary to know the number of revolutions of the disc A in a second. For this purpose an endless screw on the rod T transmits the motion to a wheel, *a*, with 100 teeth. On this wheel, which moves by one tooth for every turn of the disc, there is a catch, P, which at each complete revolution moves one tooth of a second wheel, *b* (fig. 152). On the axis of these wheels there are two needles, which move round dials represented in fig. 168. One of these indices gives the number of turns of the disc A, the other the number of hundreds of turns. By means of two screws, D and C, the wheel *a* can be uncoupled from the endless screw.

Since the sound rises in proportion to the velocity of the disc A, the wind is forced until the desired sound is produced. The same current is kept up for a certain time, two minutes for example, and the number of turns read off. This number multiplied by 18, and divided by 120, indicates the number of vibrations in a second.

With the same velocity the syren gives the same sound in air as in water; the same is the case with all gases; and it appears, therefore, that any given sound depends on the number of vibrations, and not on the nature of the sounding body.

The buzzing and humming noise of certain insects is not vocal, but is produced by very rapid flapping of the wings against the air or the body. The syren has been ingeniously applied to count the velocity of the undulations thus produced, which is effected by bringing it into unison with the sound. It has thus been found that the wings of a gnat flap at the rate of 15,000 times in a second.

223. **Bellows.**—In acoustics a *bellows* is an apparatus by which wind instruments, such as the syren and organ pipes, are worked. Between the four legs of a table there is a pair of bellows, S (fig. 171), which is worked by means of a pedal, P. D is a reservoir of flexible leather, in which is stored the air forced in by the bellows. If this reservoir is pressed by means of weights on a rod, T, moved by the hand, the air is driven through a pipe, E, into a chest, C, fixed on the

table. In this chest there are small holes closed by leather valves, which can be opened by pressing on keys in front of the box. The syren or sounding pipe is placed in one of these holes.

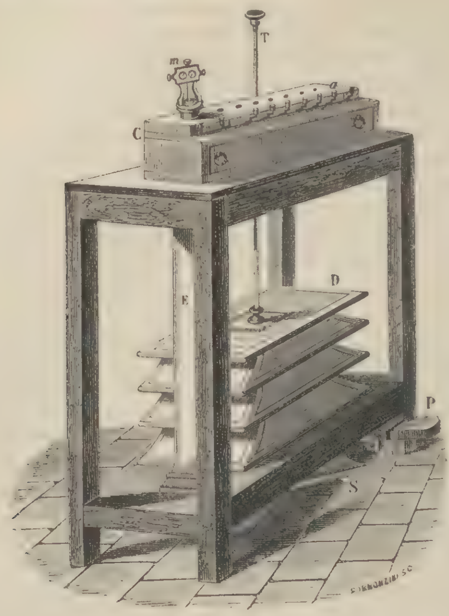


Fig. 171.

224. **Limit of perceptible sounds.**—Before Savart's researches, physicists assumed that the ear could not perceive a sound when the number of single vibrations was below 32 for deep sounds, or above 18,000 for acute sounds. But he showed that these limits were much too close, and that the faculty of perceiving sounds depends rather on their intensity than on their height; so that when extreme sounds are not heard, it arises from the fact that they have not been produced with sufficient intensity to affect the organ of hearing.

By increasing the diameter of the toothed wheel, and consequently the amplitude and intensity of the vibrations, Savart pushed the limit of acute sounds to 48,000 single vibrations in a second.

For deep sounds, he substituted for the toothed wheel an iron bar about two feet long, which revolved on a horizontal axis between two thin wooden plates, about 0·08 of an inch from the bar. As often as the bar passed, a grave sound was produced, due to the displacement of the air. As the motion became accelerated, the sound became continuous, very grave and deafening. By this means Savart found, that with 14 to 16 single vibrations in a second, the ear perceived a distinct but very deep sound.

M. Despretz, however, who has investigated the same subject, disputes Savart's results as to the limits of deep sounds, and holds that no sound is audible that is made by less than 32 single vibrations per second. On the other hand, he maintains that acute sounds are audible up to those corresponding to 73,700 single vibrations per second.

225. **Duhamel's graphic method.**—When the syren or Savart's wheel is used to determine the exact number of vibrations corresponding to a given sound, it is necessary to bring the sound which they produce into unison with the given sound, and this cannot be done exactly unless the experimenter have a practised ear. M. Duhamel's graphic method is very simple and exact, and free from this difficulty. It consists in fixing a fine point to the body emitting the sound, and causing it to trace the vibrations on a properly prepared surface.

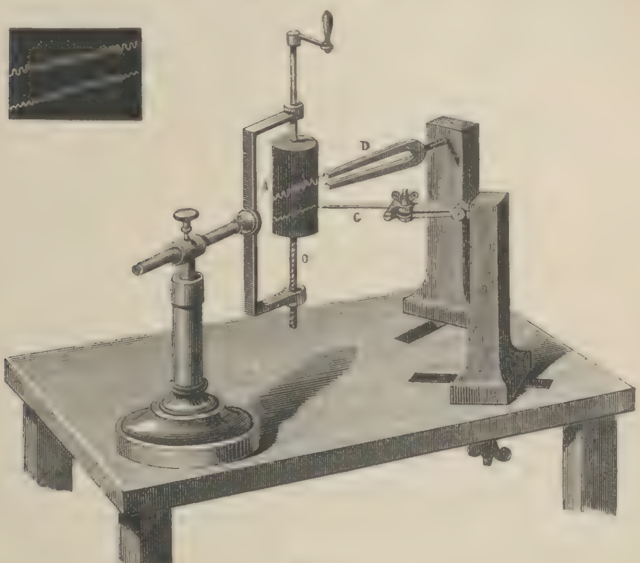


Fig. 172.

The apparatus consists of a wood or metal cylinder, A, fig. 172, fixed to a vertical axis, O, and turned by a handle. The lower part of the axis is a screw working in a fixed nut, so that, according as the handle is turned from left to right, or from right to left, the cylinder is raised or depressed. Round the cylinder is rolled a sheet of paper covered with an inadhesive film of lampblack. On this film the vibrations register themselves. This is effected as follows: Suppose the body emitting the note to be a steel rod. It is held firmly at one end, and carries at the other a fine point which grazes the surfaces of the cylinder. If the rod is made to vibrate and the cylinder is at rest, the point would describe a short line; but if the cylinder is turned, the point produces an *undulating trace*,

containing as many undulations as the point has made vibrations. Consequently the number of vibrations can be counted. It remains only to determine the time in which the vibrations were made.

There are several ways of doing this. The simplest is to compare the curve traced by the vibrating rod with that traced by a tuning-fork (231), which gives a known number of vibrations per second—for example, 500. One prong of the fork is furnished with a point, which is placed in contact with the lampblack. The fork and the rod are then set vibrating together, and each produces its own undulating trace. When the paper is unrolled, it is easy by counting the number of vibrations each has made in the same distance to determine the number of vibrations made per second by the elastic rod. Suppose, for instance, that the tuning-fork made 150 vibrations, while the rod made 165 vibrations. Now we already know that the tuning-fork makes one vibration in the $\frac{1}{500}$ part of a second, and therefore 150 vibrations in $\frac{150}{500}$ of a second. But in the same time the rod makes 165 vibrations, therefore it makes one vibration in the $\frac{150}{500 \times 165}$ of a second, and hence it makes per second $\frac{500 \times 165}{150}$ or 550 vibrations.

CHAPTER III.

THE PHYSICAL THEORY OF MUSIC.

226. **Properties of musical tones.**—A simple musical tone results from a continuous rapid isochronous vibration, provided the number of the vibrations falls within the very wide limits mentioned in the last chapter (224). Musical tones are in most cases compound. The distinction between a simple and a compound musical tone will be explained later in the chapter. The tone yielded by a tuning-fork furnished with a proper resonance box is *simple*; that yielded by a wide-stopped organ pipe, or by a flute, is nearly simple; that yielded by a musical string is compound.

Musical tones have three leading qualities, namely, *pitch*, *intensity*, and *timbre* or *colour*.

i. The *pitch* of a musical tone is determined by the number of vibrations per second yielded by the body producing the tone.

ii. The *intensity* of the tone depends on the *extent* of the vibrations. It is greater when the extent is greater, and less when it is less. It is, in fact, nearly or exactly proportional to the square of the extent or amplitude of the vibrations which produce the tone.

iii. The *timbre* is that peculiar quality of tone which distinguishes a note when sounded on one instrument from the same note when sounded on another. Thus when the C of the treble stave is sounded on a violin, and on a flute, the two notes will have the same pitch, that is, are produced by the same number of vibrations per second, and they may

have the same intensity, and yet the two tones will have very distinct qualities, that is, their timbre is different. The cause of the peculiar timbre of tones will be considered later in the chapter.

227. **Musical intervals.**—Let us suppose that a musical tone, which for the sake of future reference we will denote by the letter C, is produced by m vibrations per second; and let us further suppose that any other musical tone, X, is produced by n vibrations per second, n being greater than m; then the interval from the note C to the note X is the ratio $n : m$, the interval between two notes being obtained by *division*, not by *subtraction*. Although two or more tones may be separately musical, it by no means follows that when sounded together they produce a pleasurable sensation. On the contrary, unless they are *concordant* the result is harsh, and usually unpleasing. We have therefore to enquire what *notes* are fit to be sounded together. Now when musical tones are compared, it is found that if they are separated by an interval of 2 : 1, 4 : 1, etc., they so closely resemble one another that they may for most purposes of music be considered as the same tone. Thus, suppose c to stand for a musical note produced by $2m$ vibrations per second, and then C and c so closely resemble one another as to be called in music by the same name. The interval from C to c is called an *octave*, and c is said to be an *octave* above C, and conversely C an octave below c. If we now consider musical sounds that do not differ by an octave, it is found that if we take three notes, X, Y, and Z, resulting respectively from p, q, and r vibrations per second, these three notes when sounded together will be concordant if the ratio of $p : q : r$ equals 4 : 5 : 6. Three such notes form a *harmonic triad*, and if sounded with a fourth note, which is the octave of X, constitute what is called in music a *major chord*. Any of the notes of a chord may be altered by one or more octaves without changing its distinctive character; for instance, C, E, G, and c are a chord, and C, c, e, g, form the same chord.

If, however, the ratio $p : q : r$ equals 10 : 12 : 15, the three sounds are slightly dissonant, but not so much so as to disqualify them from producing a pleasing sensation, at least under certain circumstances. When these three notes and the octave to the lower are sounded together they constitute what in music is called a *minor* chord.

228. **The musical scale.**—The series of sounds which connects a given note, C, with its octave, c, is called the diatonic scale or gamut. The notes composing it are denoted by the letters C, D, E, F, G, A, B. The scale is then continued by taking the octaves of these notes, namely, c, d, e, f, g, a, b, and again the octaves of these last, and so on.

The notes are also denoted by names, viz. *do*, *re*, *mi*, *fa*, *sol*, *la*, *si*, *do*. The relations existing between the notes are these:—C, E, G, form a major triad, G, B, d, form a major triad, and F, A, c, form a major triad. C, G, and F have, for this reason, special names, being called respectively, the *tonic*, *dominant*, and *sub-dominant*, and the three triads the *tonic*, *dominant*, and *sub-dominant* triads or chords respectively. Consequently, the numerical relations between the notes of the scale will be given by the three proportions—

$$C : E : G :: 4 : 5 : 6$$
$$G : B : 2D :: 4 : 5 : 6$$
$$F : A : 2C :: 4 : 5 : 6$$

Hence if m denotes the number of double vibrations corresponding to the note C, the number of vibrations corresponding to the remaining notes will be given by the following table—

C	D	E	F	G	A	B	*c*
m	$\frac{9}{8}m$	$\frac{5}{4}m$	$\frac{4}{3}m$	$\frac{3}{2}m$	$\frac{5}{3}m$	$\frac{15}{8}m$	$2m$

The intervals between the successive notes being respectively—

C to D	D to E	E to F	F to G	G to A	A to B	B to *c*
$\frac{9}{8}$	$\frac{10}{9}$	$\frac{16}{15}$	$\frac{9}{8}$	$\frac{10}{9}$	$\frac{9}{8}$	$\frac{16}{15}$

It will be observed here that there are three kinds of intervals, $\frac{9}{8}$, $\frac{10}{9}$, and $\frac{16}{15}$: of these the two former are called a *tone*, the last a *semitone*. The two tones however are not identical, but differ by an interval of $\frac{81}{80}$, which is called a *comma*. Two notes which differ by a *comma* can be readily distinguished by an educated ear. The interval between the tonic and any note is denominated by the position of the latter note in the scale; thus the interval from C to G is a fifth. The scale we have now considered is called the *major* scale, as being formed of *major* triads. If the minor triad were substituted for the major, a scale would be formed that could be strictly called a *minor* scale. As scales are usually written, however, the *ascending* scale is so formed that the tonic bears a minor triad, the dominant and self-dominant bear *major* triads, while in the *descending* scale they all bear *minor* triads. Practically, in musical composition, the dominant triad is always *major*. If the ratios given above are examined, it will be found that in the major scale the interval from C to E equals $\frac{5}{4}$, while in the minor scale it equals $\frac{6}{5}$. The former interval is called a major third, the latter a *minor* third. Hence the major third exceeds the minor third by an interval of $\frac{25}{24}$. This interval is called a semitone, though very different from the interval above called by that name.

A complete discussion of the number of notes, and the intervals between them, will be found in an article by Mr. Ellis, in vol. xiii. of the *Proceedings of the Royal Society* (p. 93), 'On a Perfect Musical Scale.'

229. **On semitones and on scales with different keynotes.**—It will will be seen from the last article that the term 'semitone' does not denote a constant interval, being in one case equivalent to $\frac{16}{15}$ and in another to $\frac{25}{24}$. It is found convenient for the purposes of music to introduce notes intermediate to the seven notes of the gamut; this is done by increasing or diminishing those notes by an interval of $\frac{25}{24}$. When a note (say C) is increased by this interval, it is said to be sharpened, and is denoted by the symbol C♯, called 'C sharp;' that is $C\sharp \div C = \frac{25}{24}$. When it is decreased by the same interval, it is said to be flattened, and is represented thus—B♭, called 'B flat;' that is, $B \div B\flat = \frac{25}{24}$. If the effect of this be examined, it will be found that the number of notes in the scale from C up to *c*

has been increased from seven to twenty-one notes, all of which can be easily distinguished by the ear. Thus, reckoning C to equal 1, we have—

C	C♯	D♭	D	D♯	E♭	E	etc.
1	$\frac{25}{24}$	$\frac{27}{25}$	$\frac{9}{8}$	$\frac{75}{64}$	$\frac{6}{5}$	$\frac{5}{4}$	etc.

Hitherto we have made the note C the tonic or *key note*. Any other of the twenty-one distinct notes above mentioned, e.g. G, or F, or C♯, etc. may be made the key note, and a scale of notes constructed with reference to it. This will be found to give rise in each case to a series of notes, some of which are identical with those contained in the series of which C is the key note, but most of them different. And of course the same would be true for the minor scale as well as for the major scale, and indeed for other scales which may be constructed by means of the fundamental triads.

230. **On musical temperament.**—The number of notes that arise from the construction of the scales described in the last article is enormous; so much so as to prove quite unmanageable in the practice of music; and particularly for music designed for instruments with fixed notes, such as the pianoforte. Accordingly it becomes practically important to reduce the number of notes, which is done by slightly altering their just proportions. This process is called *temperament*. By tempering the notes, however, more or less dissonance is introduced, and accordingly several different systems of temperament have been devised for rendering this dissonance as slight as possible. The system usually adopted —at least in intention—is called the system of *equal temperament*. It consists in the substitution between C and *c* of eleven notes at equal intervals, each interval being, of course, the twelfth root of 2, or 1·05946. By this means the distinction between the semitones is abolished, so that, for example, C♯ and D♭ become the same note. The scale of twelve notes thus formed is called the *chromatic scale*. It of course follows that major triads become slightly dissonant. Thus, in the diatonic scale, if we reckon C to be 1, E is denoted by 1·25000, and G by 1·50000. On the system of equal temperament, if C is denoted by 1, E is denoted by 1·25992 and G by 1·49831.

231. **The number of vibrations producing each note. The tuning-fork.**—Hitherto we have denoted the number of vibrations corresponding to the note C by m, and have not assigned any numerical value to that symbol. In the theory of music it is usual to assign 256 double vibrations to the middle C. This, however, is arbitrary. An instrument is in tune provided the intervals between the notes are correct, when C is yielded by any number of vibrations per second not differing much from 256. Moreover, two instruments are in tune with one another if, being separately in tune, they have any one note, for instance, C, yielded by the same number of vibrations. Consequently, if two instruments have one note (say C) in common, they can then be brought into tune jointly, by having their remaining notes separately adjusted with reference to that fundamental note. A turning-fork is an instrument yielding a constant sound, and is used as a standard for tuning musical instruments. It

consists of an elastic steel rod, bent as represented in fig. 173. It is made to vibrate either by drawing a bow across the ends, or by striking one of the legs against a hard body, or by rapidly separating the two legs by means of a steel rod, as shown in the figure. The vibration produces a note which is always the same for the same tuning-fork. The note is strengthened by fixing the tuning-fork on a box open at one end, called a *resonance box*.

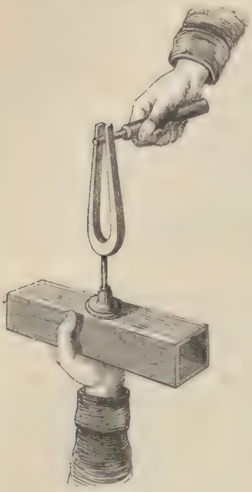


Fig. 173.

It has been remarked for some years that not only has the pitch of the tuning-fork, that is, *concert pitch*, been getting higher in the large theatres of Europe, but also that it is not the same in London, Paris, Vienna, Milan, etc. This is a source of great inconvenience both to composers and singers, and a commission was appointed to establish in France a tuning-fork of uniform pitch, and to prepare a standard which would serve as an invariable type. In accordance with the recommendations of that body, a *normal tuning-fork* has been established, which is compulsory on all musical establishments in France, and a standard has been deposited in the Conservatory of Music in Paris.

It performs 870 single vibrations per second, and gives the standard note *a*, or the *a* in the treble stave. Consequently, with reference to this standard, the middle C would result from 261 double vibrations per second.

232. **Wave length of a given note.**—Knowing the number of vibrations which a sounding body makes in a second, the corresponding wave length is easily calculated. For since sound travels at about 1,120 feet in a second, if a body only made one vibration in a second its wave length would be 1,120 feet; if it made two, the wave length would be half of 1,120 feet; if it made three, the third, and so on—that is, that *the wave length of any note is the quotient obtained by dividing the velocity of sound by the number of vibrations*; and this whatever the height of the sound, since the velocity is the same for high and low notes.

Hence, calling v the velocity of sound, l the wave length, n the number of vibrations in a second, we have $v = ln$, from which $n = \frac{v}{l}$, that is, that the number of vibrations is inversely as the wave length.

233. **On compound musical tones and harmonics.**—When any given note (say C) is sounded on most musical instruments, not that tone alone is produced, but a series of tones, each being of less intensity than the one preceding it. If C, which may be called the *primary* tone, is denoted by unity, the whole series is given by the numbers 1, 2, 3, 4, 5, 6, 7, etc.; in other words, first the primary C is sounded,

then its octave becomes audible, then the fifth to that octave, then the second octave, then the third, fifth, and a note between the sixth and seventh to the second octave, and so on. These secondary tones are called the *harmonics* of the primary *tone*. Though feeble in comparison with the primary tone, they may, with a little practice, be heard, when the primary tone is produced on most musical instruments; when, for instance, one of the lower notes is sounded on the pianoforte.

234. **Helmholtz's analysis of sound.**—For the purpose of experimentally proving the presence of the harmonics as distinct tones, Professor Helmholtz devised an instrument which he called a *resonance globe*. The principle involved in its construction is this: A volume of air contained in an open vessel, for example a bottle, when caused to vibrate, tends to yield a certain note, and consequently when that note is sounded in its neighbourhood, to strengthen it (211). A resonance globe, fig. 174, is a glass globe furnished with two openings, one of which, *a*, is turned towards the origin of the sound, and the other, *b*, by means of an india-rubber tube, is applied to the ear. If the tone proper to the resonance globe exists among the harmonics of the compound tone that is sounded, it is

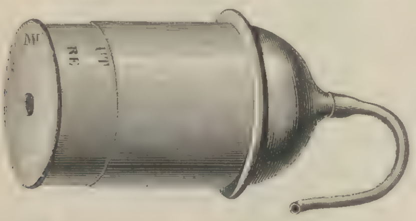


Fig. 175.

Fig. 174.

strengthened by the globe, and thereby rendered distinctly audible. Further, other things being the same, the note proper to a given globe depends on the diameter of the globe and that of the uncovered opening. Consequently, by means of a series of such globes, the whole series of harmonics in a given compound tone can be rendered distinctly audible, and their existence put beyond a doubt.

König, the eminent acoustical instrument maker, has made an important modification in the resonance globe to which he has given the form represented in fig. 175. The resonator is cylindrical, and the end which receives the sound can be drawn out, so that the volume may be increased at pleasure. As the sound thereby becomes deeper, the same resonator may be tuned to a variety of notes. On the tubulure fits a caoutchouc tube by which the vibrations may be transmitted in any direction.

235. **König's apparatus for the analysis of sound.**—As the successive application to the ear of various resonators is both slow and tedious, König has devised a remarkable apparatus in which a series of resonators act on manometric flames (263), the sounds thus become visible, and may be shown to a large auditory.

It consists of an iron frame (fig. 176) on which are fixed in two

parallel lines fourteen resonators tuned so as to give the notes from F_1 to C_5, that is to say, four octaves and a half; or notes of which the highest give the lower harmonics of the primary. On the right is a chamber C, which is supplied with coal gas by the caoutchouc tube, D, and on which are placed eight gas jets, each provided with a manometric capsule (251), (263). Each jet is connected with the chamber C by a special caoutchouc tube, while behind the apparatus a second tube connects the same jet to one of the resonators. On the right of the jets is a system of rotating mirrors identical with that described.

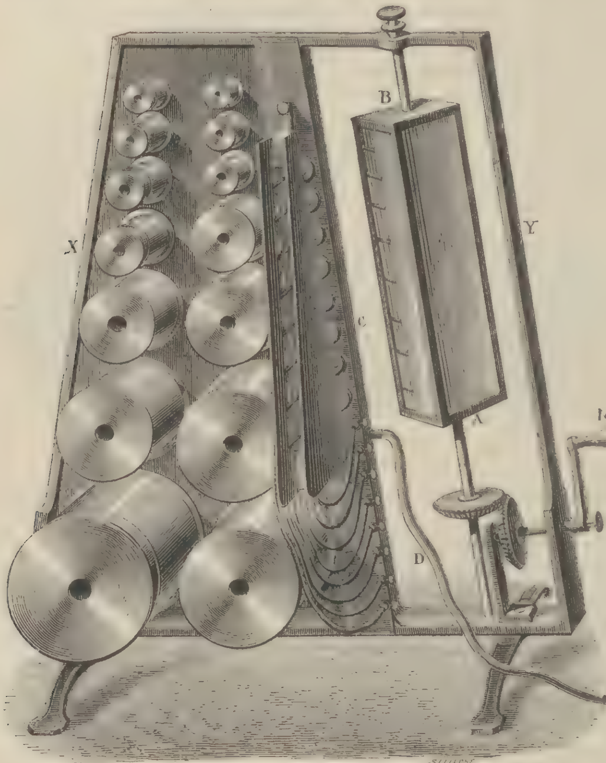


Fig. 176.

These details being understood, suppose the largest resonator on the right tuned to resound with the note 1, seven others with the harmonics of this note. Let the sound 1 be produced in part of this apparatus; if it is simple, the lower resonator alone answers, and the corresponding flame is alone dentated; but if the fundamental note is accompanied by one or more of its harmonics, the corresponding resonators speak at the same

time, which is recognised by the dentation of their flames; and thus the constituents of each sound may be detected.

236. **Synthesis of sounds.**—Not only has Helmholtz succeeded in decomposing sounds into their constituents; he has verified the result of his analysis by performing the reverse operation, the synthesis; that is, he has reproduced a given sound by combining the individual sounds of which his resonators had shown that it was composed. The apparatus which he used for this purpose consists of eleven tuning-forks, the first of which yields the fundamental note of 256 vibrations, or C_2, nine others its harmonics, while the eleventh serves as make and break to cause the diapasons to vibrate by means of electro-magnets. Each diapason has a special electro-magnet, and moreover a resonator, which strengthens it.

All these diapasons and their accessories are arranged in parallel lines of five (fig. 177) the first comprising the fundamental note and its uneven harmonics, 3, 5, 7 and 9; the second the even harmonics, 2, 4, 6, 8 and

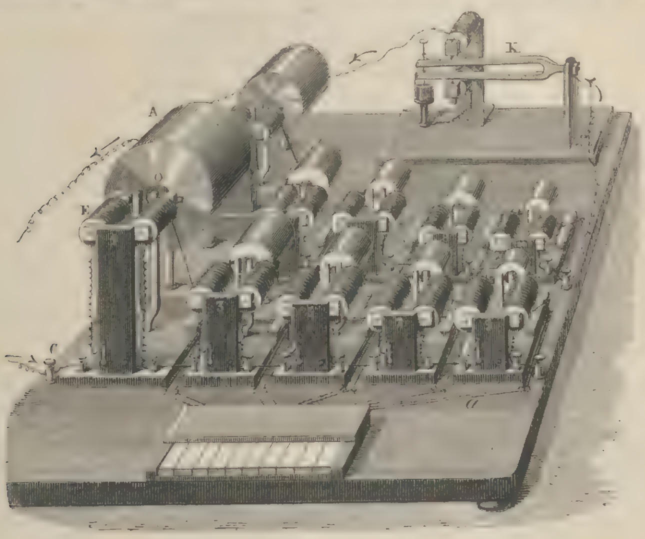


Fig. 177.

10; beyond, there is the diapason break K arranged horizontally. One of its limbs is provided with a platinum point which grazes the surface of mercury contained in a small cup, the bottom of which is connected, by a copper wire, with an electro-magnet placed in front of the diapason.

The apparatus being thus arranged, a wire from a voltaic battery is connected with the binding screw, *c*, and this with the electro-magnet, E; which in turn is connected with those of the nine following diapasons, and then with the diapason K itself. So long as the diapason does not vibrate, the current does pass, for the platinum point does not dip in the mercury cup which is connected with the other pole of the battery. But

when the diapason is made to vibrate by means of a bow, the current passes. Owing to their elasticity, the limbs of the tuning-fork soon revert to their original position, the point is no longer in the mercury, the current is broken, and so on at each double vibration of the diapason. This intermittence of the current being transmitted to all the other electro-magnets, they are alternately active and inactive. Hence they communicate to all the diapasons by their attraction the same number of vibrations. This is the case with the diapason 1 which is tuned in unison with the diapason break; but the diapason 3 being tuned to make three times as many vibrations, makes three vibrations at each break of the current; that is to say, the electro-magnet only attracts it at every third vibration; in like manner, diapason *b* only receives a fresh impulse every five vibrations, and so on.

The following is the working of the apparatus. The resonator of each diapason is closed by a clapper O (fig. 178), so that the sounds made by

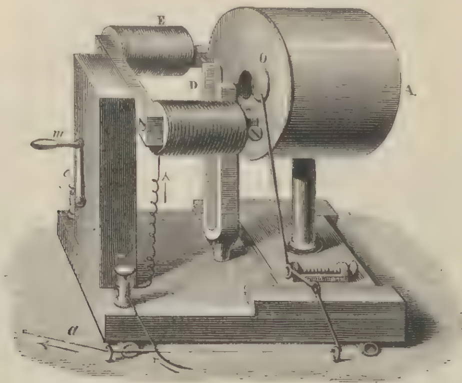


Fig. 178.

the diapasons are scarcely perceptible when the clappers are lowered. Each of these is fixed to the end of a bent lever, the shorter arm of which is worked by a cord *a*, which is connected with one of the keys of a key-board placed in front of the apparatus (fig. 177). When a key is depressed, the cord moves the lever, which raises the clapper, and the resonator then acts by strenthening its diapason. Hence by depressing any keys, we may add to the fundamental sounds any of the nine primary harmonics, and thus reproduce the sounds, the composition of which has been determined by analysis. Thus by depressing all the keys at once we obtain the sound of an open pipe in unison with the deepest diapason. By depressing the key of the fundamental notes and those of its uneven harmonics, we obtain the sound of a closed pipe.

237. **Results of Helmholtz's researches.**—By both his analytical and synthetical investigations into sounds of the most kinds, those from various musical instruments, the human voice, and even noises, Helmholtz has fully succeeded in explaining the different *timbre* or quality of

these sounds. It is due to the different intensities of the harmonics which accompany the primary tones of those sounds. The leading results of these researches into the colour of sounds may be thus stated :

i. Simple tones, as those produced by a tuning-fork with a resonance box, and by wide covered pipes, are soft and agreeable without any roughness, but weak, and in the deeper notes dull.

ii. Musical sounds accompanied by a series of harmonics, say up to the sixth, in moderate strength are full and musical. In comparison with simple tones they are grander, richer, and more sonorous. Such are the sounds of open organ pipes, of the pianoforte, etc.

iii. If only the uneven harmonics are present, as in the case of narrow covered pipes, of pianoforte strings struck in the middle, clarionets, etc. the sound becomes indistinct ; and when a greater number of harmonics are audible, the sound acquires a nasal character.

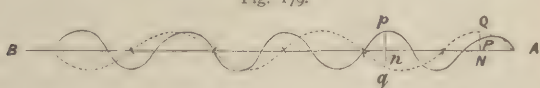
iv. If the harmonics beyond the sixth and seventh are very distinct, the sound becomes sharp and rough. If less strong, the harmonics are not prejudicial to the musical usefulness of the notes. On the contrary, they are useful as imparting character and expression to the music. Of this kind are most stringed instruments, and most pipes furnished with tongues, etc. Sounds in which the harmonics are particularly strong acquire thereby a peculiarly penetrating character ; such are those yielded by brass instruments.

238. **Perception of sounds.**—Without giving an account of the anatomy of the ear we may state succinctly how Helmholtz explains the perception by the ear of the most complicated sounds.

The recent observations of M. Costa have shown that the inner membrane of the cochlea is lined with about 3,000 minute fibres, which are the terminations of the acoustic nerve. Each fibre being tuned like a small resonator for a particular note only vibrates in unison with this note, and is deaf for all others. Hence each simple sound only causes one fibre to vibrate, while compound fibres cause several. Thus, however complicated the external sounds may be, these microscopic fibres can analyse it, and reveal the constituents of which it is formed.

239. **Beats.**—When two simple tones are sounded together, it is in many cases found that they alternately strengthen and weaken one an-

Fig. 179.



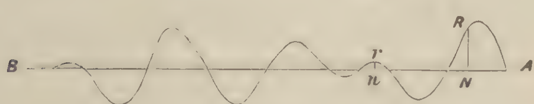


Fig. 180.

other. When this is so, they are said to *beat* with one another. This may be explained as follows : Suppose AB, in fig. 179, to be a row of particles

transmitting the sound; suppose the vibrations producing the one tone to be indicated by the continuous curved line; then, on the one hand, the ordinates of the different points of AB give the velocities with which those points are *simultaneously* moving, and, on the other hand, each point will have *successively* the different velocities represented by the successive ordinates. In like manner let the dotted line show the vibrations which produce the second tone. And, for the sake of distinctness, suppose the number of vibrations per second producing the former tone to be to that producing the latter in the ratio of 3 : 2. Now let us consider any point which when at rest occupies the position N; draw the ordinate cutting the former curve in P and the latter in Q. If the tones were sounded separately, the velocity of N at a given instant produced by the former tone would be PN, and that of N at the same instant produced by the latter tone would be QN. Consequently, as they are sounded together, N's actual velocity at the given instant is the sum of these, or PN + QN. If at the same instant we consider the point n, its velocity will consist of pn and nq jointly, but as these are in opposite directions, its actual amount will be $pn - nq$. Hence the actual velocity resulting from the coexistence of the two tones will be indicated by the curve in fig. 180, whose ordinates equal the (algebraical) sum of the corresponding ordinates of the two curves in fig. 179; that is, if AN, An, . . . represent equal distances in both figures, the curve is described by taking RN equal to PN + QN, rn equal to $pn - qn$, and so on. This curve shows by its successive ordinates the simultaneous velocities of the different particles of AB, and the successive velocities of each particle. Consequently it also represents the successive velocities communicated to the drum of the ear. An inspection of the figure will show that the velocities are first great, then small, then great, and so on, the drum being first moved rapidly for a short time, then for a short time nearly brought to rest, and so on. In short, the effect of the beating of tones on the ear as compared with that of a continuous tone is strictly analogous to the effect produced on the eye by a flickering as compared with a steady light.

It may be proved that when two simple tones are produced by m and n double vibrations per second, they produce $m - n$ beats per second; thus, if C is produced by 128, and D by 144 double vibrations per second, they will on being sounded together produce 16 beats per second. It has been ascertained that the beats produced by two tones are not audible unless the ratio $m : n$ is less than the ratio 6 : 5. Hence, in the case represented by fig. 180, though the alternations of intensity exist, they would not be audible. Also, if the tones have very different intensities, the intensity of the beat is very much disguised.

It is found that when beats are fewer than 10 per second or more than 70 per second they are disagreeable, but not to the extent of producing discord. Beats from 10 to 70 per second may be regarded as the source of all discord in music, the maximum of dissonance being attained when about 30 beats are produced per second. For example, if c and B are sounded together, the effect is very discordant, the interval between those notes being 16 : 15, so that the beats are audible, and the number of

beats per second being 16. On the other hand, if C, E, and G are sounded together there is no dissonance, but if C, E, G, B are sounded together the discord is very marked, since C produces *c*, which is discordant with B. It will be remarked that C, E, G is a major triad, while E, G, B is a minor triad.

A compound musical tone, being composed of simple tones represented by 1, 2, 3, 4, 5, 6, 7, etc., does not give rise to any simple tones capable of producing an audible beat up to the seventh — the six and seventh are the first that produce an audible beat. It is for this reason that there is no trace of roughness in a compound tone, unless the seventh harmonic be audible.

If we were to represent graphically a compound tone, we should proceed to construct a curve out of simple tones of different intensities in the same manner as fig. 180 is constructed from two simple tones of equal intensity represented by fig. 179. It is evident that the resulting curve will take different *forms* according to the presence or absence of different harmonics and their different intensities; in other words, the *colour* of the notes produced by different instruments will depend upon the *form* of the vibrations producing the sound.

240. **Combinational tones.**—Besides the beats produced when two musical notes are sounded together, there is another and distinct phenomenon, which may be thus described: Suppose two simple tones to be simultaneously produced by vibrations of finite extent, and of n and m vibrations per second. It has been shown by Helmholtz that they generate a series of other tones. The principal one of these, which may be called the *differential tone*, is produced by $n - m$ vibrations per second. Its intensity is generally very small, but it is distinctly audible in beats. It has been called the *grave harmonic*, as generally its pitch is much lower than that of the notes by which it is generated. It has been supposed to be caused by the beats becoming too numerous to be distinguished, and coalescing into a continuous sound, and this supposition was countenanced by the fact that its pitch is the same as the beat number. The supposition is shown to be erroneous, first, by the existence of the differential tones for intervals that do not beat, and secondly, by the fact that, under certain circumstances, both the beats and the differential tones may be heard together.

241. **The physical constitution of musical chords.**—Let us suppose two compound tones to be sounded together, say C and G, then we obtain two series of tones each consisting of a primary and its harmonics, namely, denoting C by 4, the two series, 4, 8, 12, 16, . . . and 6, 12, 18, 24, etc. Now, if instead of producing the two notes C and G, we had sounded the octave below C, we should have produced the series, 2, 4, 6, 8, 10, 12, 14, 16, 18, etc. It is plain that the two former series when joined differ from the last in the following respects: (*a*) The primary tone 2 is omitted. (*b*) In the case of the last series, the consecutive tones continually decrease in intensity, whereas in the two former series, 4 and 6 are of the same intensity, 8 is of lower intensity, but the two 12's will strengthen each other, and so on. (*c*) Certain of the har-

monics of the primary 2 are omitted, for example, 10, 14, etc., do not occur in either of the two former series. In spite of these differences, however, the two compound notes affect the ear in a manner very closely resembling a single compound tone; in short, they coalesce into a single tone with an artificial colour. It may be added that in the case above taken C and G produce as a combination tone 2 (that is, $6-4$), so that, strictly speaking, the 2 is not wanted in the series produced by C and G, only it exists in very diminished intensity. The same explanation will apply to all possible chords; for example, in the case of the major chord, C, E, G, we have a tone of artificial colour expressed by the series of simple tones, 4, 5, 6, 8, 10, 12, 15, 16, 18, etc., together with the combination tones, 1, 1, 2. It will be remarked that in the whole of this series there are no dissonant tones introduced, except 15, 16, and 16, 18, and this dissonance will be inappreciably slight, since 15 is the third harmonic of 5, and the 16 the fourth harmonic of 4, so that their intensities will be different, as also will be the intensities of 16 and 18. On the other hand, nearly all the tones which form a *natural* compound tone are present, namely, there are 1, 2, 4, 5, 6, 8, 10, 12, etc., in place of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, etc. In short, the major triad differs only from a *natural* compound tone in that it consists of a series of simple tones of different intensities, and omits those which by beating with its neighbouring tone would produce dissonance, for example, 7, which would beat with 6 and 8; 9, which would beat with 8 and 10; and 11, which would beat with 10 and 12. It is this circumstance which renders the major chord of such great importance in harmony. If the constituents of the minor chord are similarly discussed, namely, three compound tones whose primaries are proportional to 10, 12, 15, it will be found to differ from the major chord in the following principal respects: (*a*) The primary of the natural tone to which it approximates is very much deeper than that of the corresponding major chord. (*b*) It introduces the *differential* tones, 2, 3, 5, which form a major chord. Now it has already been remarked that when a major and minor chord are sounded together they are distinctly dissonant; for example, when C, E, G, A are sounded together. Accordingly, the fact of the differential tones forming a major chord shows that an elementary dissonance exists in every minor chord.

CHAPTER IV.

VIBRATIONS OF STRETCHED STRINGS, AND OF COLUMNS OF AIR.

242. **Vibrations of strings.**—By a *string* is meant the string of a musical instrument, such as a violin, which is stretched by a certain force, and is commonly of catgut or is a metallic wire. The vibrations which strings experience may be either *transversal* or *longitudinal*, but practically the former are alone important. *Transversal vibrations* may be produced by drawing a bow across the string, as in the case of the violin;

or by striking the string, as in the case of the pianoforte; or by pulling them transversely, and then letting them go suddenly, as in the case of the guitar and the harp.

243. **Sonometer.**—The *sonometer* is an apparatus by which the transverse vibrations of strings may be studied. It is also called *monochord*, because it has generally only one string. In addition to the string, it consists of a thin wooden box to strengthen the sound; on this there are two fixed bridges, A and D (fig. 181), over which passes the string, which

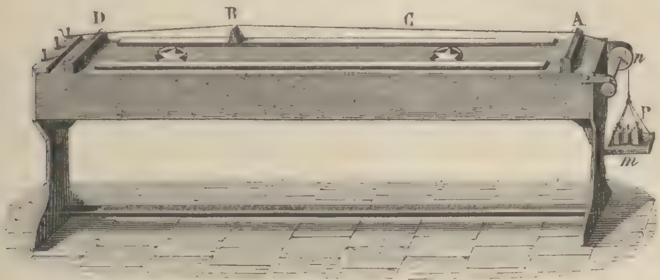


Fig. 181.

is commonly a metallic wire. This is fastened at one end, and stretched at the other by a weight, P, which can be increased at will. By means of a third movable bridge, B, the length of that portion of the wire which is to be put in vibration can be altered at pleasure.

244. **Laws of the transverse vibrations of strings.**—If l be the length of a string, that is, the vibrating part between two bridges, A and B (fig. 181), r the radius of the string, d its density, P the stretching weight, and n the number of vibrations per second, it is found by calculation that $n = \frac{1}{2rl}\sqrt{\frac{P}{\pi d}}$; π being the ratio of the circumference to the diameter. If c denote the length of the string or wire whose weight is the same as the stretching weight, it is plain that $P = \pi r^2 cdg$, where g is the accelerating force of gravity. On substituting this value for P, we find that $n = \frac{\sqrt{cg}}{2l}$. If c and l are measured in inches, and the value of the accelerating force of gravity at Paris (386·18 in seconds and inches) be used, this formula takes the shape in which it is usually written :—

$$n = \frac{9{\cdot}8257 \times \sqrt{c}}{l}$$

From the above formula the following laws have been deduced :—

I. *The tension being constant, the number of vibrations per second is inversely as the length.*

II. *The number of vibrations per second is inversely as the radius of the string.*

III. *The number of vibrations per second is directly as the square root of the stretching weight or tension.*

IV. *The number of vibrations per second of a string is inversely as the square root of its density.*

These laws are applied in the construction of stringed instruments, in which the length, diameter, tension, and substance of the strings are so chosen, that given notes may be produced from them.

245. **Experimental verification of the laws of the transverse vibration of strings.**—*Law of the lengths.* In order to prove this law, we may call to mind that the relative numbers of vibrations of the notes of the gamut are

C	D	E	F	G	A	B	C
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2

If now the entire length of the sonometer be made to vibrate, and then, by means of the bridge B, the lengths $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, $\frac{1}{2}$, which are the inverse of the above numbers, be successively made to vibrate, all the notes of the gamut are successively obtained, which proves the first law.

Law of the radius. This law is verified by stretching upon the sonometer two cords of the same material, the diameters of which are as 3 to 2, for instance. When these are made to vibrate, the second cord gives the *fifth* above the other; which shows that it makes three vibrations while the first makes two.

Law of the tensions. Having placed on the sonometer two identical strings, they are stretched by weights which are as 4 : 9. The second now gives the fifth of the first, from which it is concluded that the numbers of their vibrations are as 2 : 3, that is, as the square roots of the tensions. If the two weights are as 16 to 25, the major third or $\frac{5}{4}$ would be obtained.

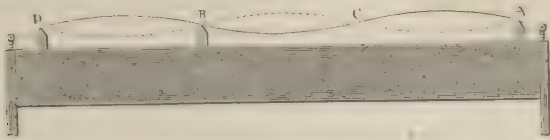
Law of the densities. Two strings of the same radius but different densities are fixed on the sonometer. Having been subjected to the same stretching weight, the position of the movable bridge on the denser one is altered until it is in unison with the other string. If then d and d' are the densities of the two strings, and l and l' the lengths which vibrate in unison, we find $\frac{l}{l'} = \frac{\sqrt{d}}{\sqrt{d'}}$. But as we know from the first law that $\frac{l}{l'} = \frac{n'}{n}$, we have $\frac{n'}{n} = \frac{\sqrt{d}}{\sqrt{d'}}$, which verifies this law.

246. **Nodes and loops.**—Let us suppose the string AD (fig. 182) to begin vibrating, the ends A and D being fixed, and while it is doing so, let a point, B, be brought to rest by a stop, and let us suppose DB to be one-third part of AD. The part DB must now vibrate about B and D as fixed points in the manner indicated by the continuous and dotted lines; now all parts of the same string tend to make a vibration in the same time; accordingly, the part between A and B will not perform a single vibration, but will divide into two at the point C, and vibrate in the manner shown in the figure. If BD were one-fourth part of AD (fig. 183), the part AB would be subdivided at C and C′ into three vibrating portions each equal to BD. The points B, C, C′ are called *nodes* or *nodal points*; the middle point of the part of the string between any two conse-

cutive nodes is called a *loop* or a *ventral segment*. It will be remarked that the ratio of BD : BA must be that of some two whole numbers, for example, 1 : 2, 1 : 3, 2 : 3, etc., otherwise the nodes cannot be formed, since the two portions of the string cannot then be made to vibrate in the same time, and the vibrations will interfere with and soon destroy one another.

If now we refer to fig. 182, the existence of the node at C can be easily proved by bending some light pieces of paper, and placing them on the

Fig. 182.



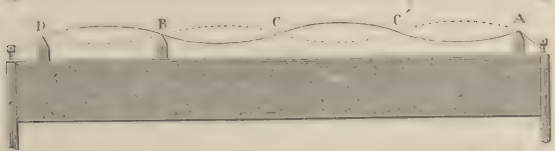


Fig. 183.

string. Say three pieces, one at C and the others respectively midway between B and C, and between C and A. The one at C experiences only a very slight motion, and remains in its place, thereby proving the existence of a node at C; the other two are violently shaken, and in most cases thrown off the string.

When a musical string vibrates between fixed points A and B, its motion is not quite so simple as might be inferred from the above description. In point of fact, partial vibrations are soon produced, and superimposed upon the primary vibrations. The partial vibrations correspond to the half, third, fourth, etc. parts of the string. It is by these partial vibrations that the harmonics are produced which accompany the primary note due to the primary vibrations.

247. **Wind instruments.**—In the cases hitherto considered the sound results from the vibrations of solid bodies, and the air only serves as a vehicle for transmitting them. In wind instruments, on the contrary, when the sides of the tube are of adequate thickness, the enclosed column of air is the sonorous body. In fact, the substance of the tubes is without influence on the primary tone; with equal dimensions it is the same whether the tubes are of glass, of wood, or of metal. These different materials simply do no more than give rise to different harmonics, and impart a different quality to the compound tone produced.

In reference to the manner in which the air in tubes is made to vibrate, wind instruments are divided into *mouth* instruments and *reed* instruments.

248. **Mouth instruments.**—In mouth instruments all parts of the mouthpiece are fixed. Fig. 184 represents the mouthpiece of an organ

pipe, and fig. 185 that of a whistle, or of a flageolet. In both figures, the aperture *ib* is called the mouth ; it is here that air enters the pipe : *b* and *o* are the *lips*, the upper one of which is bevelled. The mouthpiece is fixed at one end of a tube, the other end of which may be either opened or closed. In fig. 185 the tube can be fitted on a wind-chest by means of the foot P.

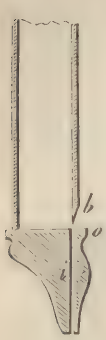


Fig. 184.

Fig. 185.

When a rapid current of air enters by the mouth, it strikes against the upper lip, and a shock is produced which causes the air to issue from *bo* in an intermittent manner. In this way, pulsations are produced which, transmitted to the air in the pipe, make it vibrate, and a sound is the result. In order that a pure note may be produced, there must be a certain relation between the form of the lips and the magnitude of the mouth ; the tube also ought to have a great length in comparison with its diameter. The number of vibrations depends in general on the dimensions of the pipe, and the velocity of the current of air.

249. **Reed instruments.**—In reed instruments a simple elastic tongue sets the air in vibration. The tongue, which is either of metal or of wood, is moved by a current of air. The mouthpieces of the oboe, the bassoon, the clarionet, the child's trumpet, are different applications of the reed, which, it may be remarked, is seen in its simplest form in the Jew's harp. Some organ pipes are reed pipes, others are mouth pipes.

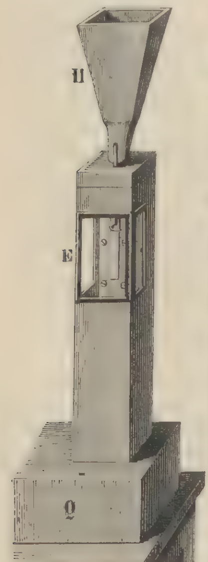


Fig. 186.

Fig. 187.

Fig. 188.

Fig. 186 represents a model of a reed pipe as commonly shown in lectures. It is fixed on the wind-chest Q of a bellows, and the vibrations of the reed can be seen through a piece of glass, E, fitting into the sides A wooden horn, H, strengthens the sound.

Fig. 187 shows the reed out of the pipe. It consists of four pieces ; 1st, a rectangular wooden tube closed below and open above at *o* ; 2nd, a copper plate *cc* forming one side of the tube, and in which there is a longitudinal aperture,

through which air passes from the tube MN to the orifice *o*; 3rd, a thin elastic plate, *i*, called the tongue, which is fixed at its upper end, and which grazes the edge of the longitudinal aperture, nearly closing it; 4th, a curved wire, *r*, which presses against the tongue, and can be moved up and down. It thus regulates the length of the tongue, and determines the pitch of the note. It is by this wire that reed pipes are tuned. The reed being replaced in the pipe MN, when a current of air enters by the foot P, the tongue is compressed, it bends inwards, and affords a passage to air, which escapes by the orifice *o*. But, being elastic, the tongue regains its original position, and performing a series of oscillations, successively opens and closes the orifice. In this way sonorous waves result and produce a note, whose pitch increases with the velocity of the current.

In this reed the tongue vibrates alternately before and behind the aperture, merely grazing the edges, as is seen in the harmonium, concertina, etc.; such a reed is called a *free reed*. But there are other reeds, called *beating reeds*, in which the tongue, which is larger than the orifice, strikes against the edges at each oscillation. The reed of the clarionet, represented in fig. 188, is an example of this; it is kept in its place by the pressure of the lips. The reeds of the hautboy and bassoon are also of this kind.

250. **Of the tones produced by the same pipe.**—Daniel Bernouilli discovered that the same organ pipe can be made to yield a succession of tones by properly varying the force of the current of air. The results he arrived at may be thus stated:—

i. If the pipe is open at the end opposite to the mouthpiece, then, denoting the primary tone by 1, we can, by gradually increasing the force of the current of air, obtain successively the tones 2, 3, 4, 5, etc., that is to say, the *harmonics* of the primary tone.

ii. If the pipe is closed at the end opposite to the mouthpiece, then, denoting the primary tone by 1, we can, by gradually increasing the force of the current of air, obtain successively the tones 3, 5, 7, etc., that is to say, the uneven *harmonics* of the primary tone.

It must be added that if a closed and an open pipe yield the same primary tone, the closed pipe must be half the length of the open pipe, if in other respects they are the same.

In any case it is impossible to produce from the given pipe a tone not included in the above series respectively.

Although the above laws are enunciated with reference to an organ pipe, they are of course true of any other pipe of uniform section.

251. **On the nodes and loops of an organ pipe.**—The vibrations of the air producing a musical tone take place in a direction parallel to the axis of the pipe—not transversely, as in the case of the portions of a vibrating string. In the former case, however, as well as in the latter, the phenomena of *nodes* and *loops* may be produced. But now by a *node* must be understood a section of the column of air contained in the pipe, where the particles remain at rest, but where there are rapid alternations of *condensation* and *rarefaction*. By a *loop* or *ventral segment* must be

understood a section of the column of air contained in the pipe where the vibrations of the particles of air have the greatest amplitudes, and where there is no change of density. The sections of the column of air are, of course, made at right angles to its axis. When the column of air is divided into several vibrating portions, it is found that the distance between any two consecutive loops is constant, and that it is bisected by a node. We can now consider separately the cases of the open and closed pipes.

i. In the case of a stopped pipe, the bottom is always a node, for the layer of air in contact with it is necessarily at rest, and only undergoes variations in density. At the mouthpiece, on the contrary, where the air has a constant density, that of the atmosphere, and the vibration is at its maximum, there is always a loop. In any stopped pipe there is at least

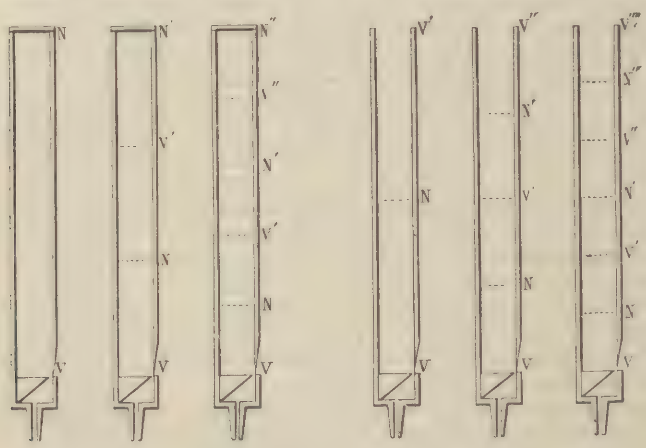


Fig. 189. Fig. 190. Fig. 191. Fig. 192. Fig. 193. Fig. 194.

one node and one loop (fig. 189); the pipe then yields its fundamental note, and the distance VN from the loop to the node is equal to half a condensed or rarefied wave length.

If the current of air be forced, the mouthpiece always remains a loop, and the bottom a node, the column divides into three equal parts (fig. 190) and an intermediate node and loop are formed. The sound produced is the first harmonic. When the second harmonic (5) is produced, there are two intermediate nodes and two loops, and the tube is then subdivided into five equal parts (fig. 191), and so on.

ii. In the case of the open pipe, whatever tone it produces, there must be a loop at each end, since the inclosed column of air is in contact with the external air at those points. When the primary tone is produced, there will be a loop at each end, and a node at the middle section of the pipe, the nodes and loops dividing the column into *two* equal parts (fig. 192). When the first harmonic (2) is produced, there will be a loop

at each end, and a loop in the middle, the column being divided into *four* equal parts by the alternate loops and nodes (fig. 193). When the second harmonic (3) is produced, the column of air will be divided into *six* equal parts by the alternate nodes and loops, and so on (fig. 194). It will be remarked that the successive modes of division of the vibrating column are the only ones compatible with the alternate recurrence at equal intervals of nodes and loops, and with the occurrence of a loop at each end of the pipe.

There are several experiments by which the existence of nodes and loops can be shown.

Fig. 195.

Fig. 196.

Fig. 197.

(*a*) If a fine membrane is stretched over a pasteboard ring, and has sprinkled on it some fine sand, it can be gradually let down a tube, as shown in fig. 197. Now suppose the tube to be producing a musical note. As the membrane descends, it will be set in vibration by the vibrating air. But when it reaches a node it will cease to vibrate, for there the air is at rest. Consequently the grains of sand, too, will be at rest, and their quiescence will indicate the position of the node. On the other

hand, when the membrane reaches a loop, that is, a point where the amplitude of the vibrations of the air attains a maximum, it will be violently agitated, as will be shown by the agitation of the grains of sand. And thus the positions of the loops can be rendered manifest.

(*b*) Again, suppose a pipe to be constructed with holes bored in one of its sides, and these covered by little doors which can be opened and shut, as shown in fig. 195. Let us suppose the little doors to be shut and the pipe to be caused to produce such a tone that the nodes are at N and N′ and the loops at V, V′, V″. At the latter points the density is that of the external air, and consequently if the door at V′ is opened no change is produced in the note. At the former points N and N′ there are alternately condensation and rarefaction taking place. If now the door at N′ is opened, this alternation of density is no longer possible, for the density at this open point must be the same as that of the external air, and consequently N′ becomes a loop and the note yielded by the tube is changed. The change of notes produced by changing the fingering of the flute is, of course, one form of this experiment.

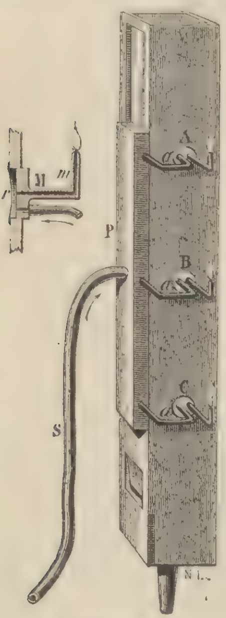


Fig. 198.

(*c*) Suppose A, in fig. 196, to be a pipe emitting a certain note, and suppose P to be a plug, fitting the tube, fastened to the end of a long rod by which it can be forced down the tube. Now when the plug is inserted, whatever be its position, there will be a node in contact with it. Consequently, as it is gradually forced down, the note yielded by the pipe will keep on changing. But every time it reaches a position which was occupied by a node before its insertion, the note becomes the same as the note originally yielded. For now the column of air vibrates in exactly the same manner as it did before the plug was put in.

(*d*) Fig. 198 shows another mode of illustrating the same point which is identical in principle with König's manometric flames. The figure represents an organ pipe, on one side of which is a chest, P, filled with coal gas, by means of the tube S. The gas from the chest comes out in three jets, A, B, C, and is then ignited. The manner in which the gas passes from the chest to the point of ignition is shown in the smallest figure, which is an enlarged section of A. A circular hole is bored in the side of the pipe and covered with a membrane, *r*. A piece of wood is fitted into the hole so as to leave a small space between it and the membrane. The gas passes from the chest, in the direction indicated by the arrow, into the space between the membrane and the piece of wood, and so out by the tube *m*, at the mouth of which it is ignited. Now suppose the pipe to be caused to

yield its primary note, then as it is an uncovered pipe there ought to be a node at B, its middle point. Consequently there ought to be rapid changes of density at B; these would cause the membrane r to vibrate, and thereby blow out the flame m, and this is what actually happens. If by increasing the force of the wind the octave to the primary note is produced, B will be a loop, and A and C nodes. Consequently the flames at A and C will now be extinguished, as is, in point of fact, the case. But at B, there being no change of density, the membrane is unmoved, and the flame continues to burn steadily.

By each and all of these experiments it is shown that in a given pipe, whether open or closed, there are always a certain number of nodes, and midway between any two consecutive nodes there is always a *loop* or *ventral point*.

252. **Explanation of the existence of nodes and loops in a musical pipe.**—The existence of nodes and loops is to be explained by the co-existence in the same pipe of two equal waves travelling in contrary directions.

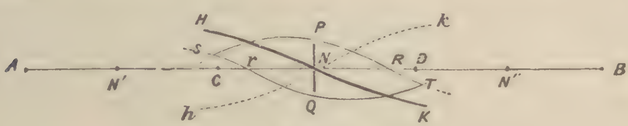


Fig. 199.

Let A be a point from which a series of waves sets out towards B, and let the length of these waves, whether of condensation or rarefaction, be AC, CD, or DB. And let B be the point from which the series of exactly equal waves sets out towards A. It must be borne in mind that in the case of a wave of condensation originating at A, the particles move in the direction A to B, but in a wave of condensation originating at B they move in the direction B to A. Now let us suppose that condensation at C, caused by the wave from A, begins at the same instant that condensation caused by the wave from B begins at D. Consequently, restricting our attention to the particles in the line CD, at any instant the velocities of the particles in CD due to the former wave will be represented by the ordinates of the curve SPRT, while those due to the wave from B will be represented by the co-ordinates of the curve TQrS. Then, since the waves travel with the same velocity and are at C and D respectively at the same instant, we must have, for any subsequent instant, CR equal to Dr. If, therefore, N is the middle point between C and D, we must have rN equal to RN, and consequently PN equal to QN, that is to say, if the particle at N transmitted only one vibration, its motion at each instant would be in the opposite phase to that of its motion if it transmitted only the other vibration. In other words, the particle N will at every instant tend to be moved with equal velocity in opposite directions by the two waves, and therefore will be *permanently* at rest. That point is therefore a *node*. In like manner there is a node at N′ midway between A and C, and also at N″ midway between B and D. In regard to the motion of

the remaining particles, it is plain that their respective velocities will be the (algebraical) sum of the velocities they would at each instant receive from the waves separately. Hence at the instant indicated by the diagram they are given by the ordinates of the curve HNK. This curve will change from instant to instant, and at the end of the time occupied by the passage of a wave of condensation (or of rarefaction) from C to D will occupy the position shown by the dotted line hNk. Hence it is evident that particles near N have but small changes of velocity, whilst those near C and D experience large changes of velocity.

If the curve HK were produced both ways, it would always pass through N′ and N″; the part, however, between N and N′ would sometimes be on one side and sometimes on the other side of AB. Hence all the particles between N′ and N have, simultaneously, first a motion in the direction A to B, and then a motion in the direction B to A, those particles near C having the greatest amplitude of vibrations. Hence near N and N′ there will be alternately the greatest condensation and rarefaction.

This explanation applies to the case in which AB is the axis of an open organ pipe, A being the end where the mouthpiece is situated. The waves from B have their origin in the reflection of the series of waves from A. In the particular case considered, the note yielded by the pipe is that indicated by 3, that is, the fifth above the octave to the primary note. A similar explanation can obviously be applied to all other cases, and whether the end be opened or closed. But in the latter case the series of waves from the closed end must commence at a point distant from the mouthpiece by a space equal to one-half, or three halves, or five halves, etc. of the length of a wave of condensation or expansion.

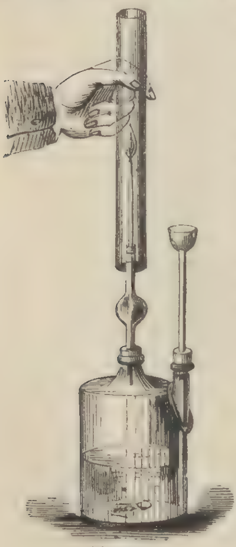


Fig. 200.

253. **Chemical harmonicon.**—The air in an open tube may be made to give a sound by means of a luminous jet of hydrogen, coal gas, etc. When a glass tube about 12 inches long is held over a lighted jet of hydrogen (fig. 200), a note is produced, which, if the tube is in a certain position, is the fundamental note of the tube. The sounds, doubtless, arise from the successive explosions produced by the periodic combinations of the atmospheric oxygen with the issuing jet of hydrogen. The apparatus is called the *chemical harmonicon.*

The phenomena of the chemical harmonicon and of singing flames have been investigated by Prof. Tyndall, whose *Lectures on Sound* contain a number of very beautiful experiments on this subject.

The note depends on the size of the flame and the length of the tube: with a long tube, by varying the position of

the jet in the tube, the series of notes in the ratio 1 : 2 : 3 : 4 : 5 is obtained.

If, while the tube emits a certain sound, the voice or the syren (222) be gradually raised to the same height, as soon as the note is nearly in unison with the harmonicon, the flame becomes agitated, jumps up and down, and is finally steady when the two sounds are in unison. If the tone of the syren is gradually heightened, the pulsations again commence; they are the optical expressions of the beats (239) which occur near perfect unison.

If, while the jet burns in the tube and produces a note, the position of the tube is slightly altered, a point is reached at which no sound is heard. If now the voice, or the syren, or the tuning-fork, be pitched at the note produced by the jet, it begins to sing, and continues to sing even after the syren is silent. A mere noise, or shouting at an incorrect pitch, affects the flame, but does not cause it to sing.

254. **Stringed instruments.**—Stringed musical instruments depend on the production of transverse vibrations. In some, such as the piano, the sounds are *constant*, and each note requires a separate string: in others, such as the violin and guitar, the sounds are *varied* by the fingering, and can be produced by fewer strings.

In the piano the vibrations of the strings are produced by the stroke of the *hammer*, which is moved by a series of bent levers communicating with the keys. The sound is strengthened by the vibrations of the air in the sounding board on which the strings are stretched. Whenever a key is struck, a *damper* is raised which falls when the finger is removed from the key and stops the vibrations of the corresponding string. By means of a *pedal* all the dampers can be simultaneously raised, and the vibrations then last for some time.

The harp is a sort of transition from the instruments with constant to those with variable sounds. Its strings correspond to the natural notes of the scale: by means of the pedals the lengths of the vibrating parts can be changed, so as to produce sharps and flats. The sound is strengthened by the sounding box, and by the vibrations of all the strings harmonic with those played.

In the violin and guitar each string can give a great number of sounds, according to the length of the vibrating part, which is determined by the pressure of the fingers of the left hand while the right hand plays the bow, or the strings themselves. In both these instruments the vibrations are communicated to the upper face of the sounding box, by means of the bridge over which the strings pass. These vibrations are communicated from the upper to the lower face of the box, either by the sides or by an intermediate piece call the *sound post*. The air in the interior is set in vibration by both faces, and the strengthening of the sound is produced by all these simultaneous vibrations. The value of the instrument consists in the perfection with which all possible sounds are intensified, which depends essentially on the quality of the wood, and the relative arrangement of the parts.

255. **Wind instruments.**—All wind instruments may be referred to

the different types of sounding tubes which have been described. In some, such as the organ, the notes are *fixed*, and require a separate pipe for each note : in others the notes are *variable*, and are produced by only one tube : the flute, horn, etc. are of this class.

In the organ the pipes are of various kinds, namely, mouth pipes, open and stopped, and reed pipes with apertures of various shapes. By means of *stops* the organist can produce any note by both kinds of pipe.

In the *flute*, the mouthpiece consists of a simple lateral circular aperture ; the current of air is directed by means of the lips, so that it grazes the edge of the aperture. The holes at different distances are closed either by the fingers or by keys ; when one of the holes is opened, a loop is produced in the corresponding layer of air, which modifies the distribution of nodes and loops in the interior, and thus alters the note. The whistling of a key is similarly produced.

The *pandæan pipe* consists of tubes of different sizes corresponding to the different notes of the gamut.

In the trumpet, the horn, the trombone, cornet-à-piston, and ophicleide, the lips form the reed, and vibrate in the mouthpiece. In the *horn*, different notes are produced by altering the distance of the lips. In the *trombone*, one part of the tube slides within the other, and the performer can alter at will the length of the tube, and thus produce higher or lower notes. In the *cornet-à-piston*, the tube forms several convolutions : pistons placed at different distances can, when played, cut off communication with other parts of the tube, and thus alter the length of the vibrating column of air.

CHAPTER V.

VIBRATIONS OF RODS, PLATES, AND MEMBRANES.

256. **Vibrations of rods.**—Rods and narrow plates of wood, of glass, and especially of tempered steel, vibrate in virtue of their elasticity ; like strings they have two kinds of vibrations, longitudinal and transverse. The latter are produced by fixing the rods at one end, and passing a bow over the free part. Longitudinal vibrations are produced by fixing the rod at any part, and rubbing it in the direction of its length with a piece of cloth sprinkled with resin. But in the latter case the sound is only produced when the point of the rod at which it has been fixed is some aliquot part of its length, as a half, a third, or a quarter.

It is shown by calculation that *the number of transverse vibrations made in a given time by rods and thin plates of the same kind is directly as their thickness, and inversely as the square of their length.* The width of the plate does not affect the number of vibrations. A wide plate, however, requires a greater force to set it in motion than a narrow one. It is, of course, understood that one end of the vibrating plate is held firmly.

In elastic rods of the same kind *the number of longitudinal vibrations is inversely as their length, whatever be the diameter and form of their transverse section.*

Fig. 201 represents an instrument invented by Marloye, and known as Marloye's harp, based on the longitudinal vibration of rods. It consists of a solid wooden pedestal in which are fixed twenty thin deal rods, some coloured and others white. They are of such a length that the white rods give the diatonic scale, while the coloured ones give the half notes, and complete the chromatic scale. The instrument is played by rubbing the rods, in the direction of their length, between the finger and thumb, which have been previously covered with powdered resin. The notes produced resemble those of a pandæan pipe.

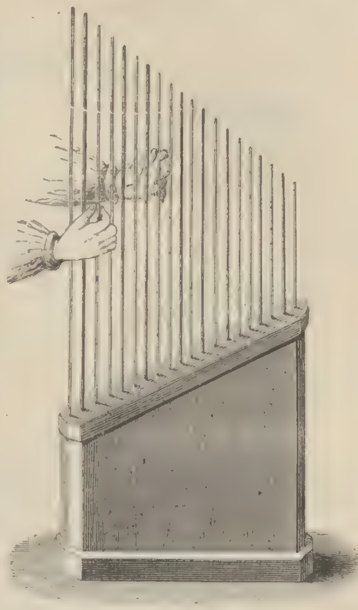


Fig. 201.

The *tuning-fork*, the *triangle*, and *musical-boxes* are examples of the transverse vibrations of rods. In musical-boxes small plates of steel of different dimensions are fixed on a rod, like the teeth of a comb. A cylinder, whose axis is parallel to this rod, and whose surface is studded with steel teeth, arranged in a certain order, is placed near the plates. By means of a clockwork motion the cylinder rotates, and the teeth striking the steel plate set them in vibration, producing a tune, which depends on the arrangement of the teeth on the cylinder.

257. **Vibrations of plates.** In order to make a plate vibrate, it is fixed in the centre (fig. 202), and a bow rapidly drawn across one of the edges; or else it is fixed at any point of its surface, and caused to vibrate by rapidly drawing a string covered with resin against the edges of a central hole (fig. 203).

Vibrating plates contain nodal lines (246), which vary in number and position according to the form of the plates, their elasticity, the mode of excitation, and the number of vibrations. These nodal lines may be made visible by covering the plate with fine sand before it is made to vibrate. As soon as the vibrations commence, the sand leaves the vibrating parts, and accumulates on the nodal lines, as seen in figs. 202 and 203.

The position of the nodal lines may be determined by touching the points at which it is desired to produce them. Their number increases

with the number of vibrations, that is, as the note given by the plates is higher. The nodal lines always possess great symmetry of form, and the same form is always produced on the same plate under the same conditions. They were discovered by Chladni.

Fig. 202.

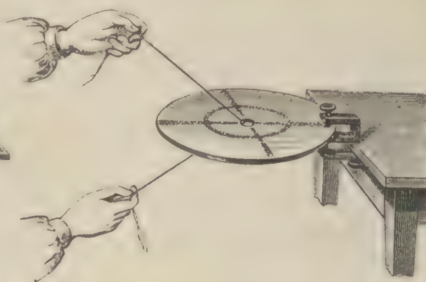


Fig. 203.

The vibrations of plates are governed by the following law: *In plates of the same kind and shape, and giving the same system of nodal lines, the number of vibrations per second is directly as the thickness of the plates, and inversely as their area.*

Gongs and *cymbals* are examples of instruments in which sounds are produced by the vibration of metallic plates. The *glass harmonicon* depends on the vibrations of glass plates.

258. **Vibrations of membranes.**—In consequence of their inflexibility, membranes cannot vibrate unless they are stretched, like the skin of a drum. The sound they give is more acute in proportion as they are smaller and more tightly stretched. To obtain vibrating membranes, Savart fastened gold-beater's skin on wooden frames.

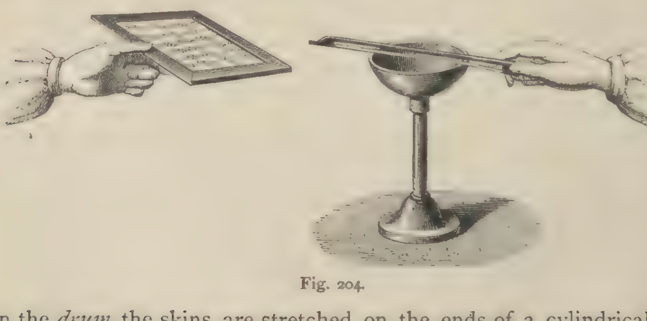


Fig. 204.

In the *drum*, the skins are stretched on the ends of a cylindrical box. When one end is struck, it communicates its vibrations to the internal

column of air, and the sound is thus considerably strengthened. The cords stretched against the lower skin strike against it when it vibrates, and produce the sound characteristic of the drum.

Membranes either vibrate by direct percussion, as in the drum, or they may be set in vibration by the vibrations of the air, as Savart has observed, provided these vibrations are sufficiently intense. Fig. 204 shows a membrane vibrating under the influence of the vibrations in the air caused by a sounding bell. Fine sand strewn on the membrane shows the formation of nodal lines just as upon plates.

There are numerous instances in which solid bodies are set in vibration by the vibrations of the air. The condition most favourable for the production of this phenomenon is, that the body to be set in vibration is under such conditions that it can readily produce vibrations of the same duration as those transmitted to it by the air. The following are some of these phenomena:

If two violoncello strings tuned in unison are stretched on the same sound-box, as soon as one of them is sounded, the other is set in vibration. This is also the case if the interval of the strings is an octave, or a perfect fifth. A violin string may also be made to vibrate by sounding a tuning-fork.

Two large glasses are taken of the same shape, and as nearly as possible of the same dimensions and weight, and are brought in unison by pouring into them proper quantities of water. If now one of them is sounded, the other begins to vibrate, even if it is at some distance, but if water be added to the latter, it ceases to vibrate.

Breguet found that if two clocks, whose time was not very different, were fixed on the same metallic support, they soon attained exactly the same time.

Membranes are eminently fitted for taking up the vibrations of the air, on account of their small mass, their large surface, and the readiness with which they subdivide. With a pretty strong whistle, nodal lines may be produced in a membrane stretched on a frame, even at the end of a large room.

The phenomenon so easily produced in easily-moved bodies is also found in large and less elastic masses; all the pillars and walls of a church vibrate more or less while the bells are being rung.

CHAPTER VI.

GRAPHICAL METHODS OF STUDYING VIBRATORY MOVEMENTS.

259. **M. Lissajous' method of making vibrations apparent.**—The method of M. Lissajous exhibits the vibratory motion of bodies either directly or by projection on a screen. It has also the great advantage that the vibratory motions of two sounding bodies may be compared *without the aid of the ear*, so as to obtain the exact relation between them.

This method, which depends on the persistence of visual sensations on the retina, consists in fixing a small mirror on the vibrating body, so as to

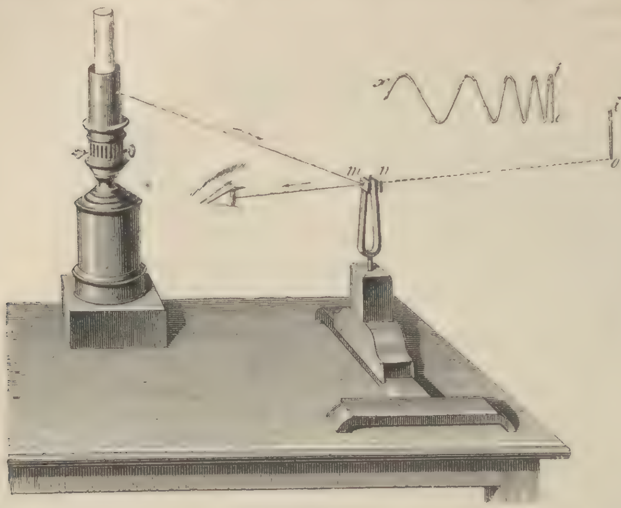


Fig. 205.

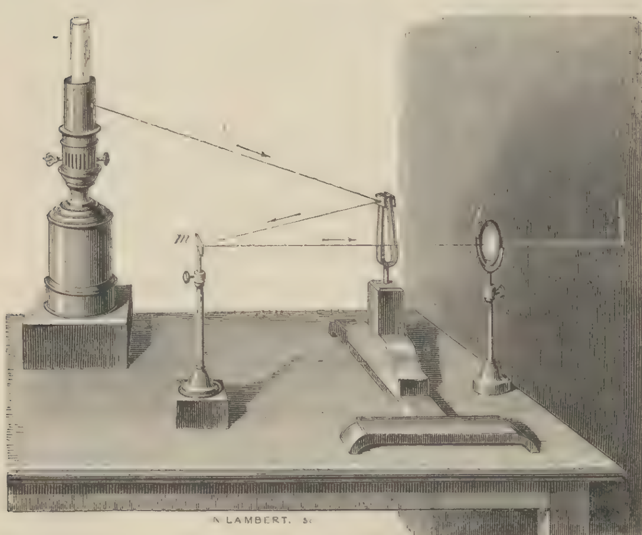


Fig. 206.

vibrate with it, and impart to a luminous ray a vibratory motion similar to its own.

M. Lissajous uses tuning-forks, and fixes to one of the prongs a small metallic mirror, *m* (fig. 205), and to the other a counterpoise, *n*, which is necessary to make the tuning-fork vibrate regularly for a long time. At a few yards' distance from the mirror there is a lamp surrounded by a dark chimney, in which there is a small hole, giving a single luminous point. The tuning-fork being at rest, the eye is placed so that the luminous point is seen at *o*. The tuning-fork is then made to vibrate, and the image elongates so as to form a persistent image, *oi*, which diminishes in proportion as the amplitude of the oscillation decreases. If, during the oscillation of the mirror, it is made to rotate by rotating the tuning-fork on its axis, a sinuous line, *oix*, is produced instead of the straight line *oi*. These different effects are explained by the successive displacements of the luminous pencil, and by the duration of these luminous impressions on the eye after the cause has ceased, a phenomenon to which we shall revert in treating of vision.

If, instead of viewing these effects directly they are projected on the screen, the experiment is arranged as shown in fig. 206, the pencil reflected from the vibrating mirror is reflected a second time from a fixed mirror, *m*, which sends it towards an achromatic lens, *l*, placed so as to project the images on the screen.

260. **Combination of two vibratory motions in the same direction.**—M. Lissajous has resolved the problem of the optical combination of

Fig. 207.

two vibratory motions—vibrating at first in the same direction, and then at right angles to each other.

Fig. 207 represents the experiment as arranged for combining two parallel motions. Two tuning-forks provided with mirrors are so arranged that the light reflected from one of them reaches the other, which is almost parallel to it, and is then sent towards a screen after having passed through a lens.

If now the first tuning-fork alone vibrates, the image on the screen is the same as in experiment 207: but if they both vibrate supposing they are in unison, the elongation increases or diminishes according as the simultaneous motions imparted to the image by the vibrations of the mirrors do or do not coincide.

If the tuning-forks pass their position of equilibrium in the same time, and in the same direction, the image attains its maximum ; and the image is at its minimum when they pass at the same time but in opposite directions. Between these two extreme cases the amplitude of the image varies according to the time which elapses between the exact instant at which the tuning-forks pass through their position of rest respectively. The ratio of this time to the time of a double vibration is called a *difference of phase* of the vibration.

If the tuning-forks are exactly in unison, the luminous appearance on the screen experiences a gradual diminution of length in proportion as the amplitude of the vibration diminishes ; but if the pitch of one is very little altered, the magnitude of the image varies periodically, and, while the beats resulting from the imperfect harmony are distinctly heard, the eyes see the concomitant pulsations of the image.

261. **Optical combination of two vibratory motions at right angles to each other.**—The optical combination of two rectangular vibratory motions is effected as shown in the figure 208, that is, by means of two tuning-forks, one of which is horizontal and the other vertical, and both pro-

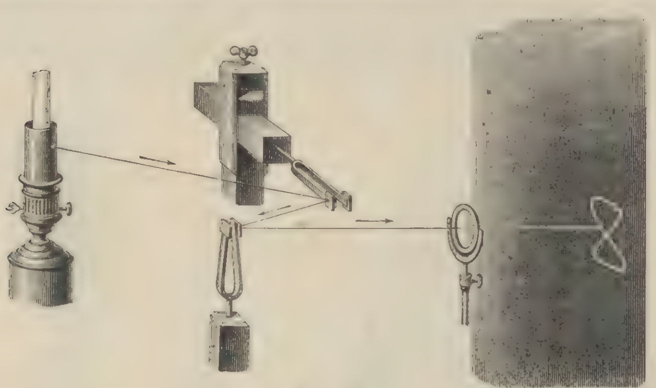


Fig. 208.

vided with mirrors. If the horizontal fork first vibrates alone, a horizontal luminous outline is seen on the screen, while the vibration of the other produces a vertical image. If both tuning-forks vibrate simultaneously the two motions combine, and the reflected pencil describes a more or less complex curve, the form of which depends on the number of vibrations of the two tuning-forks in a given time. This curve gives a valuable means of comparing the number of vibrations of two sounding bodies.

Fig. 209 shows the luminous image on the screen when the tuning-forks are in unison, that is, when the number of vibrations is equal.

The fractions below each curve indicate the differences of phase between them. The initial form of the curve is determined by the difference of phase. The curve retains exactly the same form when the tuning-forks

are in unison, provided that the amplitudes of the two rectangular vibrations decrease in the same ratio.

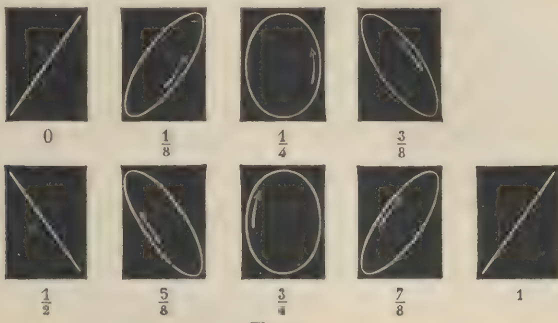


Fig. 209.

If the tuning-forks are not quite in unison, the initial difference of phase is not preserved, and the curve passes through all its variations.

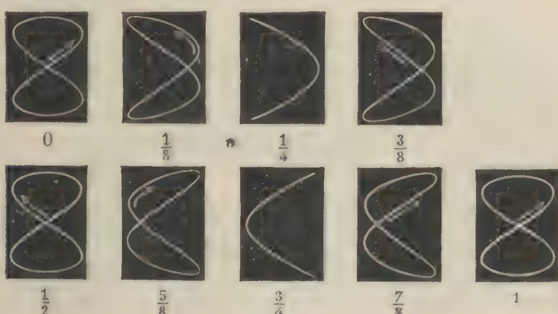


Fig. 210.

Fig. 210 represents the different appearances of the luminous image when the difference between the tuning-forks is an octave; that is, when

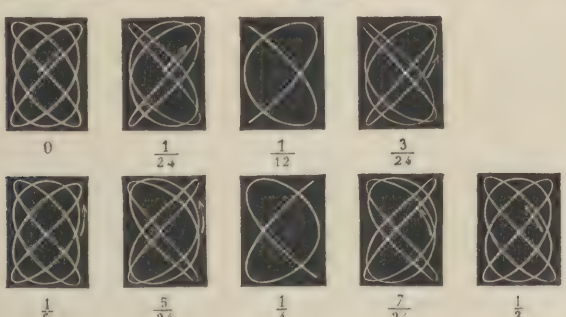


Fig. 211.

the numbers of their vibrations are as 1 : 2; and fig. 211 gives the series of curves when the numbers of the vibrations are as 3 : 4.

It will be seen that the curves are more complex when the ratios or the numbers of vibrations are less simple. M. Lissajous has examined these curves theoretically (*Annales de Physique et de Chimie*, 1857), and has calculated their general equations.

When these experiments are made with a Duboscq's photo-electrical apparatus instead of an ordinary lamp, the phenomena are remarkably brilliant.

262. **Léon Scott's Phonautograph.**—This beautiful apparatus possesses the great advantage of being able to register not only the vibrations produced by solid bodies, but also those produced by wind instruments, by the voice in singing, and even by any noise whatsoever, for

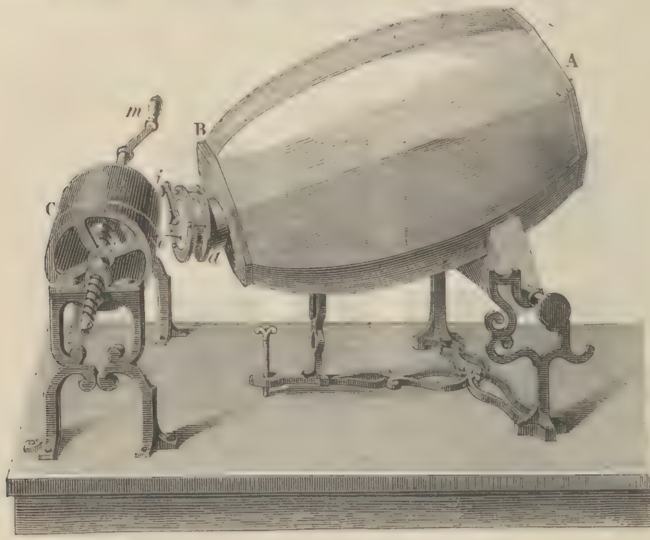


Fig. 212.

instance, that of thunder, or the report of a cannon. It consists of an ellipsoidal cask, AB, about a foot and a half long and a foot in its greatest diameter. It is made of plaster of Paris, a substance which can be made to vibrate only with difficulty, and therefore has but little tendency to deaden the vibrations of the air within it. The end A is open, but the end B is closed by a solid bottom, to the middle of which is fitted a brass tube, *a*, bent at an elbow and terminated by a ring on which is fixed a flexible membrane, either bladder or very thin india rubber. A second ring, which is forced more or less on the first by means of a screw, serves to stretch the membrane to the required amount. The tube *a* can be turned so as to be inclined at different angles to the membrane. Near the centre of the membrane, fixed by sealing-wax, is a very light

style, which, of course, shares the movements of the membrane. In order that the style might not be at a *node*, M. Scott fitted the stretching ring with a movable piece, *i*, which he calls a subdivider, and which, being made to touch the membrane first at one point and then at another, enables the experimenter to alter the arrangements of the nodal lines at will. By means of the subdivider the point is made to coincide with a loop, that is, a point where the vibrations of the membrane are at a maximum. In construction the phonautograph is very analogous to the organ of hearing, the ellipsoid corresponding to the auditory canal, the membrane to the tympanum, and the subdivider to the chain of little bones which touch the tympanum.

This being the construction, it follows that when a sound is produced near the apparatus, the air in the ellipsoid, the membrane, and the style will vibrate in unison with it, and it only remains to trace on a sensitive surface the vibrations of the style, and to fix them. For this purpose there is placed in front of the membrane a copper cylinder, C, turning round a horizontal axis by means of a handle, *m*. On the prolonged axis of the cylinder a screw is cut which works in a nut ; consequently, when the handle is turned, the cylinder gradually advances in the direction of its axis. Round the cylinder is wrapped a sheet of paper, covered with a thin layer of lampblack. The lampblack is deposited by setting the cylinder in motion, and moving beneath it a smoky flame.

The apparatus is used by bringing the prepared paper into contact with the point of the style, and then setting the cylinder in motion round its axis. So long as no sound is heard the style remains at rest, and merely removes the lampblack along a line which is a helix on the cylinder, but which becomes straight when the paper is unwrapped. But when a sound is heard, the membrane and the style vibrate in unison, and the line traced out is no longer straight, but undulates ; each undulation corresponding to a double vibration of the style. Consequently the figures thus obtained faithfully denote the number, amplitude, and isochronism of the vibrations. The figures are large if the sound is loud, very small if the sound is very weak; they are stretched out when the sound is low, squeezed together when it is high. When the sound is clear they are free and regular, feeble and irregular when it is confused. It would seem, however, that the figures do not represent the whole vibration of the membrane, but only the part of it which takes place in a direction parallel to the axis of the cylinder.

Fig. 213 shows the trace produced when a simple note is sung, and strengthened by means of its upper octave. The latter note is represented by the curve of lesser amplitude. Fig. 214 represents the sound produced jointly by two pipes whose notes differ by an octave. Fig. 215 in its lower line represents the rolling sound of the letter R when pronounced with a ring ; and fig. 216 on its lower line represents the sound produced by a tin plate when struck with the finger.

The upper lines of figs. 215 and 216 are the same, and represent the perfectly isochronous vibrations of a tuning-fork placed near the ellipsoid.

These lines were traced by a fine point on one branch of the fork, which was thus found to make exactly 500 vibrations per second. In consequence, each undulation of the upper line corresponds to the $\frac{1}{500}$ part of a second; and thus these lines become very exact means of measuring

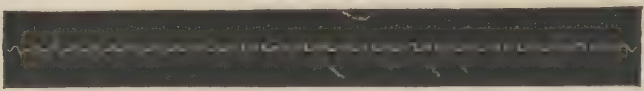


Fig. 213.

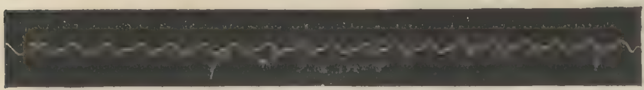


Fig. 214.

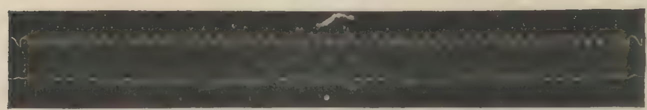


Fig. 215.

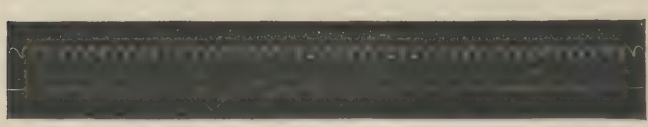


Fig. 216.

short intervals of time. For example, in fig. 215, each of the separate shocks producing the rolling sound of the letter R corresponds to about 18 double vibrations of the tuning-fork, and consequently lasts about $\frac{18}{500}$ or about $\frac{1}{28}$ of a second.

The curves once traced, it remains to fix them on the blackened paper. For this purpose, M. Scott dipped them first into a bath of pure alcohol; and when they were dry, he then dipped them into a solution of resin—for instance, sandrach—in alcohol. By this means the lampblack is perfectly fixed.

263. **König's manometric flames.**—König's method consists in transmitting the movement of the sonorous waves which constitute a sound to gas flames, which, by their pulsations, indicate the nature of the sounds. For this purpose a metallic capsule, represented in section at A, fig. 217, is divided into two compartments by a thin membrane of caoutchouc; on the right of the figure is a gas jet, and below it a tube conveying coal gas; on the left is a tubulure, to which may be attached a caoutchouc tube. The other end of this may be placed at the node of an organ pipe (251), or it terminates in a mouth-piece, in front of which a given note may be sung; this is the arrangement represented in fig. 217.

When the sound waves enter the capsule by the mouth-piece and the tube, the membrane yielding to the condensation and rarefaction of the

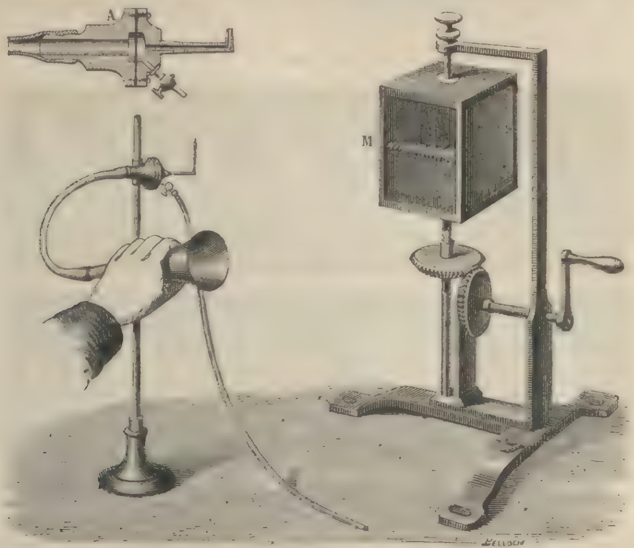


Fig. 217.

waves, the coal gas in the compartment on the right is alternately con-

Fig. 218.

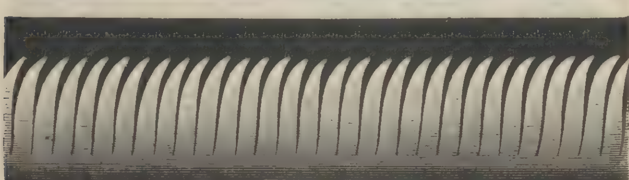
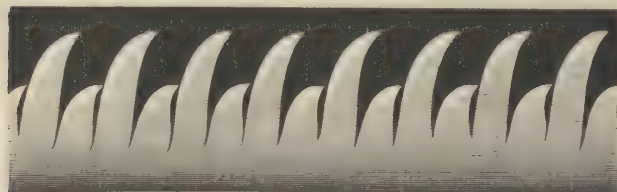


Fig. 219.

tracted and expanded, and hence are produced alternations in the length of the flame, which are, however, scarcely perceptible when the flame is

observed directly. But to render them distinct they are received on a mirror with four faces, M, which may be turned by two cog-wheels and a handle. As long as the flame burns steadily there appears in the mirror,

Fig. 220.



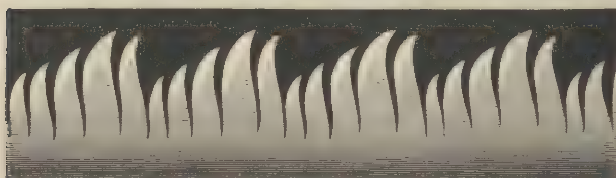
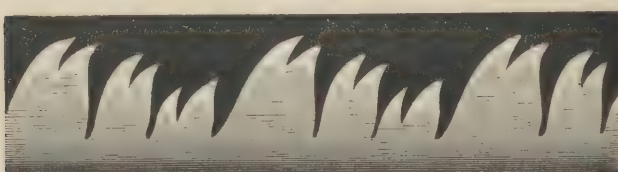


Fig. 221.

when turned, a continuous band of light. But if the capsule is connected with a sounding tube yielding the fundamental note, the image of the

Fig. 221 *a*.



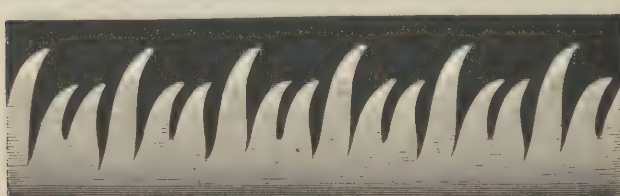
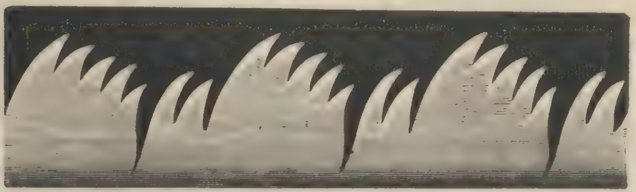


Fig. 221 *b*.

flame takes the form represented in figure 218, and that of figure 219 if the sound yields the octave. If the two sounds reach the capsule simultaneously the flame has the appearance of fig. 220 : in that case, however,

the tube leading to the capsule must be connected by a T-pipe with two sounding tubes, one giving the fundamental note, and the other the

Fig. 221*c*.



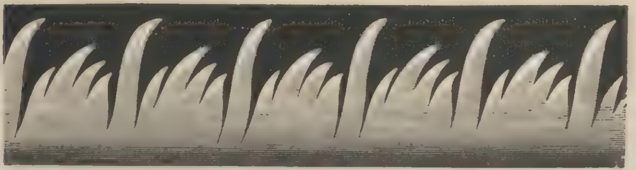


Fig. 221 *d*.

octave. If one gives the fundamental note and the other the third the flame has the appearance of figure 221.

If the vowel E be sung in front of the mouthpiece first upon *ut*, and then upon ut_2, the turning mirror gives the flames represented in figs. 221*a* and 221*b*; and by singing the vowel O on the same letters the figs. 221*c* and 221*d*.

BOOK VI.

ON HEAT.

CHAPTER I.

PRELIMINARY IDEAS. THERMOMETERS.

264. **Heat. Hypothesis as to its nature.**—In ordinary language the term *heat* is not only used to express a particular sensation, but also to describe that particular state or condition of matter which produces this sensation. Besides producing this sensation, heat acts variously upon bodies; it melts ice, boils water, makes metals red-hot, and so forth.

Two theories as to the cause of heat are current at the present time; these are the *theory of emission* and the theory of *undulation.*

On the first theory heat is caused by a subtle imponderable fluid, which surrounds the molecules of bodies, and which can pass from one body to another. These *heat atmospheres*, which thus surround the molecules, exert a repelling influence on each other, in consequence of which heat acts in opposition to the force of cohesion. The entrance of this substance into our bodies produces the sensation of warmth, its egress the sensation of cold.

On the second hypothesis the heat of a body is caused by an oscillating or vibratory motion of its material particles, and the hottest bodies are those in which the vibrations have the greatest velocity and the greatest amplitude. Hence, on this view, heat is not a *substance*, but a *condition of matter*, and a condition which can be transferred from one body to another. It is also assumed that there is an imponderable elastic ether, which pervades all bodies and infinite space, and is capable of transmitting a vibratory motion with great velocity. A rapid vibratory motion of this ether produces heat, just as sound is produced by a vibratory motion of atmospheric air, and the transference of heat from one body to another is effected by the intervention of this ether.

This hypothesis is now admitted by the most distinguished physicists; it affords a better explanation of the phenomena of heat than any other theory, and it reveals an intimate connection between heat and light. In accordance with it, heat is a *form of motion;* and it will hereafter be shown that heat may be converted into motion, and reciprocally motion may be converted into heat.

In what follows, however, the phenomena of heat will be considered, as far as possible, independently of either hypothesis; but we shall subsequently return to the reasons for the adoption of the latter hypothesis.

265. **General effects of heat.**—The general action of heat upon bodies is to develope a repulsive force between their molecules which is continually struggling with molecular attraction. Under its influence, therefore, bodies tend to *expand*—that is, to assume a greater volume; and then to *change their state of aggregation*—that is, to pass from the solid to the liquid, or from the liquid to the gaseous state.

All bodies expand by the action of heat. As a general rule gases are the most expansible, then liquids, and lastly, solids.

In solids which have definite figures, we can either consider the expansion in one dimension, or the *linear* expansion; in two dimensions, the *superficial* expansion, or in three dimensions, the *cubical* expansion or the expansion of volume, although one of these never takes place without the other. As liquids and gases have no definite figures, the expansions of volume have in them alone to be considered.

To show the linear expansion of solids, the apparatus represented in fig. 222 may be used. A metallic rod, A, is fixed at one end by a screw

Fig. 222.

B, while the other end presses against the short arm of an index, K, which moves on a scale. Below the rod there is a sort of cylindrical lamp in which alcohol is burned. The needle K is at first at the zero point, but as the rod becomes heated it expands, and moves the needle along the scale.

The cubical expansion of solids is shown by a *Gravesande's* ring. It consists of a brass ball *a* (fig. 223), which at the ordinary temperature passes freely through a ring, *m*, almost of the same diameter. But when the ball has been heated, it expands and no longer passes through the ring.

In order to show the expansion of liquids, a large glass bulb provided with a capillary stem is used (fig. 224). When the bulb and a part of the stem contain some coloured liquid, as soon as heat is applied, the liquid rapidly rises in the stem, and the expansion thus observed is far greater than in the case of solids.

The same apparatus may be used for showing the expansion of gases.

Being filled with air, a small thread of mercury is introduced into the capillary tube to serve as index (fig. 225). When the globe is heated in

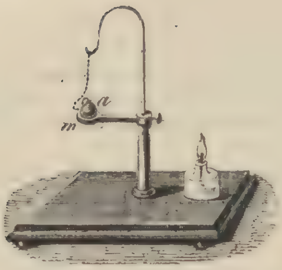


Fig. 223.

Fig. 224.

Fig. 225.

the slightest degree, even by approaching the hand, the expansion is so great that the index is driven to the end of the tube, and is finally expelled. Hence, even for a very small degree of heat, gases are highly expansible.

In these different experiments the bodies contract on cooling, and when they have attained their former temperature they resume their original volume. Certain metals, however, especially zinc, form an exception to this rule, and it appears to be also the case with some kinds of glass.

MEASUREMENT OF TEMPERATURES. THERMOMETRY.

266. **Temperature.**—The *temperature* or hotness of a body may be defined as being the greater or less extent to which it tends to impart sensible heat to other bodies. The temperature of any particular body is varied by adding to it or withdrawing from it a certain amount of sensible heat. The temperature of a body must not be confounded with the *quantity of heat* it possesses; a body may have a high temperature and yet have a very small quantity of heat, and conversely a low temperature and yet possess a large amount of heat. If a cup of water be taken from a bucketful, both will indicate the same temperature, yet the quantities they possess will be different. This subject of the quantity of heat will be afterwards more fully explained in the chapter on Specific Heat.

267. **Thermometers.**—*Thermometers* are instruments for measuring temperatures. Owing to the imperfections of our senses we are unable to measure temperatures by the sensations of heat or cold which they produce in us, and for this purpose recourse must be had to the physical action of heat on bodies. These actions are of various kinds, but the expansion of bodies has been selected as the easiest to observe. But heat also produces electrical phenomena in bodies; and on these the most delicate methods of observing temperatures have been based, as we shall see in a subsequent chapter.

Liquids are best suited for the construction of thermometers—the expansion of solids being too small, and that of gases too great. Mercury and alcohol are the only liquids used—the former because it only boils at a very high temperature, and the latter because it does not solidify at the greatest known cold.

The mercurial thermometer is the most extensively used. It consists of a capillary glass tube, at the end of which is blown the *bulb*, a cylindrical or spherical reservoir. Both the bulb and a part of the stem are filled with mercury, and the expansion is measured by a scale graduated either on the stem itself, or on a frame to which it is attached.

Besides the manufacture of the bulb, the construction of the thermometer comprises three operations; the *calibration* of the tube, or its division into parts of equal capacity, the introduction of the mercury into the reservoir, and the graduation.

268. **Division of the tube into parts of equal capacity.**—As the indications of the thermometer are only correct when the divisions of the scale correspond to equal expansions of the mercury in the reservoir, the scale must be graduated so as to indicate parts of equal capacity in the tube. If the tube were quite cylindrical, and of the same diameter throughout, it would only be necessary to divide it into equal lengths. But as the diameter of glass tubes is usually greater at one end than another, parts of equal capacity in the tube are represented by unequal lengths of the scale.

In order, therefore, to select a tube of uniform calibre, a thread of mercury about an inch long is introduced into the capillary tube, and moved in different positions in the tube, care being taken to keep it at the same temperature. If the thread is of the same length in every part of the tube, it shows that the capacity is everywhere the same; but if the thread occupies different lengths the tube is rejected, and another one sought.

269. **Filling the thermometer.**—In order to fill the thermometer with mercury, a small funnel, C (fig. 226), is blown on it at the top, and is filled with mercury; the tube is then slightly inclined, and the air in the bulb expanded by heating it with a spirit lamp. The expanded air partially escapes by the funnel, and on cooling, the air which remains contracts, and a portion of the mercury passes into the bulb D. The bulb is then again warmed, and allowed to cool, a fresh quantity of mercury enters, and so on, until the bulb and part of the tube are full of mercury. The mercury is then heated to boiling; the mercurial vapours in escaping

carry with them the air and moisture which remain in the tube. The tube, being full of the expanded mercury and of mercurial vapour, is hermetically sealed at one end. When the thermometer is cold the mercury ought to fill the bulb and a portion of the stem.

Fig. 226.

270. **Graduation of the thermometer.**—The thermometer being filled, it requires to be graduated, that is, to be provided with a scale to which variations of temperature can be referred. And, first of all, two points must be fixed which represent identical temperatures and can always be easily produced.

Experiment has shown that ice always melts at the same point whatever be the degree of heat, and that distilled water under the same pressure, and in a vessel of the same kind, always boils at the same temperature. Consequently, for the first fixed point, or zero, the temperature of melting ice has been taken; and for a second fixed point, the temperature of boiling water in a metallic vessel under the normal atmospheric pressure of 760 millimeters.

This interval of temperature, that is, the range from zero to the boiling point, is taken as the unit for comparing temperatures; just as a certain length, a foot or a yard for instance, is used as a basis for comparing lengths.

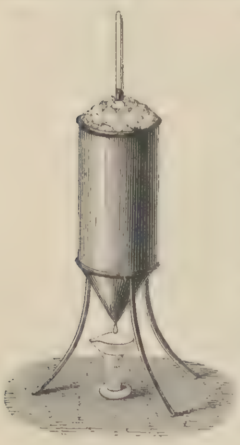


Fig. 227.

271. **Determination of the fixed points.**—To obtain zero, snow or pounded ice is placed in a vessel, in the bottom of which is an aperture by which water escapes (fig. 227). The bulb and a part of the stem of the thermometer are immersed in this for about a quarter of an hour, and a mark made at the level of the mercury which represents zero.

The second fixed point is determined by means of the apparatus represented in the figures 228 and 229, of which fig. 229 represents a vertical section. In both, the same letters designate the same parts. The whole of the apparatus is of copper. A central tube, A, open at both ends, is fixed on a cylindrical vessel containing water; a second tube, B, concentric with the first, and surrounding it, is fixed on the same vessel, M. In this second cylinder, which is closed at both ends, there are three tubulures, *a*, E, D. A cork, in which is the thermometer *t*, fits in *a*. To E a glass tube, containing

mercury, is attached, which serves as a manometer for measuring the pressure of the vapour in the apparatus. D is an escape tube for the vapour and condensed water.

The apparatus is placed on a furnace and heated till the water boils ; the vapour produced in M rises in the tube A, and passing through the two tubes in the direction of the arrows, escapes by the tubulure D. The thermometer *t* being thus surrounded with vapour, the mercury expands, and when it has become stationary, the point at which it stops is marked. This is the point sought for. The object of the second case, B, is to avoid the cooling of the central tubulure by its contact with the air.

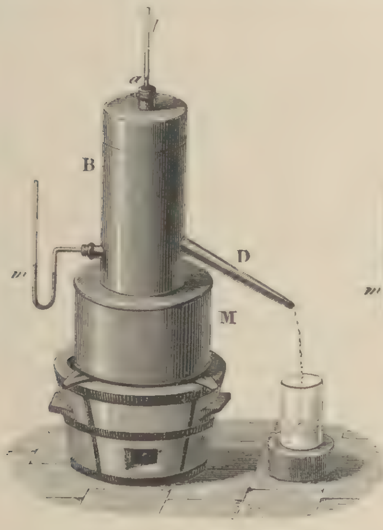


Fig. 228.

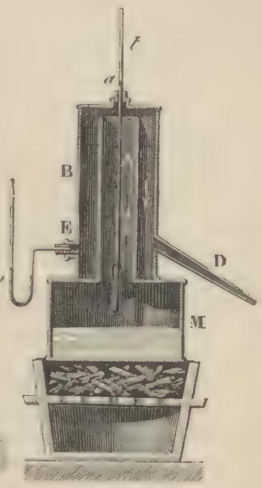


Fig. 229.

The determination of the point 100 (see next article) would seem to require that the height of the barometer during the experiment should be 760 millimeters, for when the barometric height is greater or less than this quantity, water boils either above or below 100 degrees. But the point 100 may always be exactly obtained, by making a correction introduced by M. Biot. He found that, for every 27 millimeters' difference in height of the barometer, there was a difference in the boiling point of 1 degree. If, for example, the height of the barometer is 778 that is, 18 millimeters, or two-thirds of 27, above 760—water would boil at 100 degrees and two-thirds. Consequently $100\frac{2}{3}$ would have to be marked at the point at which the mercury stops.

Gay-Lussac observed that water boils at a somewhat higher temperature in a glass than in a metal vessel : and as the boiling point is raised by any salts which are dissolved, it has been assumed that it was

necessary to use a metal vessel and distilled water in fixing the boiling point. M. Rudberg has, however, shown that these latter precautions are superfluous. The nature of the vessel, and salts dissolved in ordinary water, influence the temperature of boiling water, but not that of the vapour which is formed. That is to say, that if the temperature of boiling water from any of the above causes is higher than 100 degrees, the temperature of the vapour does not exceed 100, provided the pressure is not more than 760 millimetres. Consequently the higher point may be determined in a vessel of any material, provided the thermometer is quite surrounded by vapour, and does not dip in the water.

Even with distilled water, the bulb of the thermometer must not dip in the liquid; for it is only the upper layer that really has the temperature of 100 degrees, since the temperature increases from layer to layer towards the bottom in consequence of the increased pressure.

Fig. 230.

272. **Construction of the scale.**—Just as the foot-rule which is adopted as the unit of comparison for length is divided into a number of equal divisions called inches for the purpose of having a smaller unit of comparison, so likewise the unit of comparison of temperatures, the range from zero to the boiling point, must be divided into a number of parts of equal capacity called *degrees*. There are three modes in which this is done. On the Continent, and more especially in France, this space is divided into 100 parts, and this division is called the *Centigrade* or *Celsius* scale; the latter being the name of the inventor. The Centigrade thermometer is almost exclusively adopted in foreign scientific works, and as its use is gradually extending in this country, it has been and will be adopted in this book.

The degrees are designated by a small cipher placed a little above on the right of the number which marks the temperature, and to indicate temperatures below zero the minus sign is placed before them. Thus, -15° signifies 15 degrees below zero.

In accurate thermometers the scale is marked on the stem itself (fig. 230). It cannot be displaced, and its length remains fixed, as glass has very little expansibility. The graduation is effected by covering the stem with a thin layer of wax, and then marking the divisions of the scale, as well as the corresponding numbers, with a steel point. The thermometer is then exposed for about ten minutes to the vapours of hydrofluoric acid, which attacks the glass where the wax has been removed. The rest of the wax is then removed, and the stem is found to be permanently etched.

Besides the *Centigrade* scale two others are frequently used—*Fahrenheit's scale* and *Réaumur's scale.*

In Réaumur's scale the fixed points are the same as on the Centigrade scale, but the distance between them is divided into 80 degrees instead of into 100. That is to say, 80 degrees Réaumur are equal to 100 degrees Centigrade; one degree Réaumur is equal to $\frac{100}{80}$ or

$\frac{5}{4}$ of a degree Centigrade, and one degree Centigrade equals $\frac{80}{100}$ or $\frac{4}{5}$ degrees Réaumur. Consequently to convert any number of Réaumur degrees into Centigrade degrees (20 for example), it is merely necessary to multiply them by $\frac{5}{4}$ (which gives 25). Similarly, Centigrade degrees are converted into Réaumur by multiplying them by $\frac{4}{5}$.

The thermometric scale invented by Fahrenheit in 1714 is still much used in England, and also in Holland and North America. The higher fixed point is like that of the other scales, the temperature of boiling water, but the null point or zero is the temperature obtained by mixing equal weights of sal-ammoniac and snow, and the interval between the two points is divided into 212 degrees. The zero was selected because the temperature was the lowest then known, and was thought to represent absolute cold. When Fahrenheit's thermometer is placed in melting ice it stands at 32 degrees, and, therefore, 100 degrees on the Centigrade scale are equal to 180 degrees on the Fahrenheit scale, and thus 1 degree Centigrade is equal to $\frac{9}{5}$ degree Fahrenheit, and inversely 1 degree Fahrenheit is equal to $\frac{5}{9}$ of a degree Centigrade.

If it be required to convert a certain number of Fahrenheit degrees (95 for example) into Centigrade degrees, the number 32 must first be subtracted, in order that the degrees may count from the same part of the scale. The remainder in the example is thus 63, and as 1 degree Fahrenheit is equal to $\frac{5}{9}$ of a degree Centigrade, 63 degrees are equal to $63 \times \frac{5}{9}$ or 35 degrees Centigrade.

If F be the given temperature in Fahrenheit degrees and C the corresponding temperature in Centigrade degrees, the former may be converted into the latter by means of the formula

$$(F-32)\,\tfrac{5}{9}=C,$$

and conversely, Centigrade degrees may be converted into Fahrenheit by means of the formula

$$\tfrac{9}{5}C.+32=F.$$

These formulæ are applicable to all temperatures of the two scales, provided the signs are taken into account. Thus, to convert the temperature of 5 degrees Fahrenheit into Centigrade degrees we have

$$(5-32)\,\tfrac{5}{9}=\frac{-27\times 5}{9}=-15\ C.$$

In like manner we have for converting Réaumur into Fahrenheit degrees the formula

$$\tfrac{9}{4}R+32=F.$$

and conversely, for changing Fahrenheit into Réaumur degrees, the formula

$$(F.-32)\,\tfrac{4}{9}=R.$$

273. **Displacement of zero.**—Thermometers, even when constructed with the greatest care, are subject to a source of error which must be

taken into account: this is, that in course of time the zero tends to rise, the displacement sometimes extending to as much as 2 degrees; so that when the thermometer is immersed in melting ice it no longer sinks to zero.

This is generally attributed to a diminution of the volume of the reservoir and also of the stem, occasioned by the pressure of the atmosphere. It is usual with very delicate thermometers to fill them two or three years before they are graduated.

Besides this slow displacement, there are often variations in the position of the zero, when the thermometer has been exposed to high temperatures, caused by the fact that the bulb and stem do not contract on cooling to their original volume (265), and hence it is necessary to verify the position of zero when a thermometer is used for delicate determinations.

Regnault has found that some mercurial thermometers, which agree at 0° and at 100°, differ between these points, and that these differences frequently amount to several degrees. Regnault thinks that this is due to the unequal expansion of different kinds of glass.

274. **Limits to the employment of mercurial thermometers.**—Of all thermometers in which liquids are used, the one with mercury is the most useful, because this liquid expands most regularly, and is easily obtained pure, and because its expansion between −36° and 100° is *regular*, that is, proportional to the degree of heat. It also has the advantage of having a very low specific heat. But for temperatures below −36 C. the alcoholic thermometer must be used, for mercury solidifies at −40° C. Above 100 degrees the coefficient of expansion increases and the indications of the mercurial thermometers are only approximate, the error arising sometimes to several degrees. Mercurial thermometers also cannot be used for temperatures above 350°, for this is the boiling point of mercury.

275. **Alcohol thermometer.**—The *alcohol thermometer* differs from the mercurial thermometer in being filled with coloured alcohol. But as the expansion of liquids is less regular in proportion as they are near the boiling point, alcohol, which boils at 78° C., expands very irregularly. Hence, alcohol thermometers are usually graduated by placing them in baths at different temperatures together with a standard mercurial thermometer, and marking on the alcohol thermometer the temperature indicated by the mercurial thermometer. In this manner the alcohol thermometer is comparable with the mercurial one; that is to say, it indicates the same temperatures under the same conditions. The alcohol thermometer is especially used for low temperatures, for it does not solidify at the greatest known cold.

276. **Conditions of the delicacy of a thermometer.**—A thermometer may be delicate in two ways :—1. When it indicates very small changes of temperature. 2. When it quickly assumes the temperature of the surrounding medium.

The first object is attained by having a very narrow capillary tube and

a very large bulb; the expansion of the mercury on the stem is then limited to a small number of degrees, the 10 to 20 or 20 to 30 for instance, so that each degree occupies a great length on the stem, and can be subdivided into very small fractions. The second kind of delicacy is obtained by making the bulb very small, for then it rapidly assumes the temperature of the liquid in which it is placed.

A good mercurial thermometer should answer to the following tests: When its bulb and stem, to the top of the column of mercury, are immersed in melting ice, the top of the mercury should exactly indicate 0°C.; and when suspended with its bulb and scale immersed in the steam of water boiling in a metal vessel (as in fig. 228), the barometer standing at 760 mm., the mercury should be stationary at 100° C. When the instrument is inverted, the mercury should fill the tube, and fall with a metallic click, thus showing the complete exclusion of air. The value of the degrees should be uniform : to ascertain this, a little cylinder of mercury may be detached from the column by a slight jerk, and on inclining the tube it may be made to pass from one portion of the bore to another. If the scale be properly graduated, the column will occupy an equal number of degrees in all parts of the tube.

277. **Leslie's differential thermometer.**—Sir John Leslie constructed a thermometer for showing the difference of temperature of two neighbouring places, from which it has received the name *differential thermometer*. It consists of two glass bulbs containing air, and joined by a bent glass tube of small diameter fixed on a frame (fig. 231). Before the apparatus is sealed, a coloured liquid is introduced in sufficient quantity to fill the horizontal part of the tube, and about half the vertical legs. It is important to use a liquid which does not give off vapours at ordinary temperatures, and dilute sulphuric acid coloured with litmus is generally preferred. The apparatus being closed, the air is passed from one bulb into the other by heating them unequally until the level of the liquid is the same in both branches. A zero is marked at each end of the liquid column. To graduate the apparatus, one of the bulbs is raised to a temperature 10° higher than the other. The air of the first is expanded and causes the column of liquid *ba* to rise in the other leg. When the column is stationary, the number 10 is marked on each side at the level of the liquid, the distance between zero and 10 being divided into 10 equal parts, both above and below zero, on each leg.

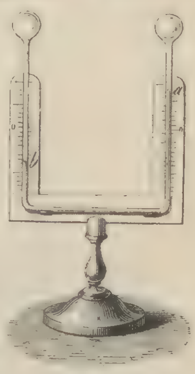


Fig. 231.

278. **Matthiessen's differential thermometer.**—Professor Matthiessen devised a form of differential thermometer which can be used for indicating the temperature of liquids, and which constitutes a valuable addition to our means of illustrating for lecture purposes many important experiments in heat. Its construction is evident from the annexed

figure (232). The bulbs are pendent, and it can therefore be readily immersed in a liquid. In a tube which connects the two limbs there is a stopcock, which is very useful as a means of adjusting the level of the liquids, a rather troublesome task with Leslie's instrument.

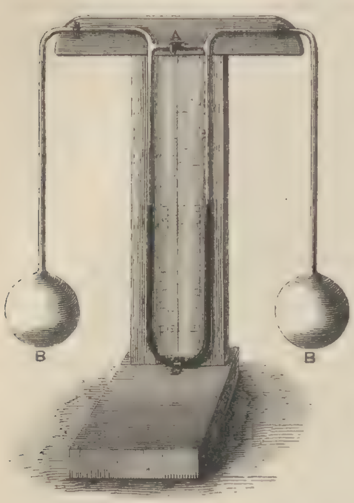


Fig. 23..

279. **Breguet's metallic thermometer.**—Breguet invented a thermometer founded on the unequal expansion of metals, and remarkable for its delicacy. It consists of three strips of platinum, gold, and silver, which are passed through a rolling mill so as to form a very thin metallic ribbon. This is then coiled in a spiral form, as seen in fig. 233, and one end being fixed to a support, a light needle is fixed to the other, which is free to move round a graduated scale.

Silver, which is the most expansible of the metals, forms the internal face of the spiral, and platinum the external. When the temperature rises, the silver expands more than gold or platinum, the spiral unwinds itself, and the needle moves from left to right of the above figure. The contrary effect is produced when the temperature sinks. The gold is placed between the other two metals, because its expansibility is intermediate between that of the silver and the platinum. Were these two metals employed alone, their rapid unequal expansion might cause a fracture. Breguet's thermometer is graduated in Centigrade degrees, by comparing it with a standard mercurial thermometer.

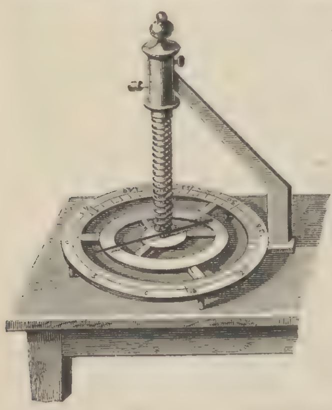


Fig. 233.

280. **Rutherford's maximum and minimum thermometers.**—It is necessary, in meteorological observations, to know the highest temperature of the day and the lowest temperature of the night. Ordinary thermometers could only give these indications by a continuous observation, which would be impracticable. Several instruments have accordingly been invented for this purpose, the simplest of which is Rutherford's. On a rectangular piece of plate glass (fig. 234) two thermometers are fixed,

whose stems are bent horizontally. The one, A, is a mercurial, and the other, B, an alcohol thermometer. In A there is a small piece of iron wire, A, moving freely in the tube, which serves as an index. The thermometer being placed horizontally, when the temperature rises the mercury pushes the index before it. But as soon as the mercury contracts

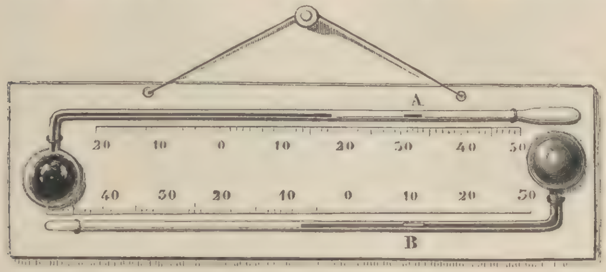


Fig. 234.

the index remains in that part of the tube to which it has been moved, for there is no adhesion between the iron and the mercury. In this way the index registers the highest temperature which has been attained ; in the figure this is 31°. In the minimum thermometer there is a small hollow glass tube which serves as index. When it is at the end of the column of liquid, and the temperature falls, the column contracts, and carries the index with it, in consequence of adhesion, until it has reached the greatest contraction. When the temperature rises, the alcohol expands, and passing between the sides of the tube and the index, does not displace B. The position of the index gives therefore the lowest temperature which has been reached : in the figure this was 9½ degrees below zero.

281. **Pyrometers.**—The name *pyrometers* is given to instruments for measuring temperatures so high that mercurial thermometers could not be used. The older contrivances for this purpose, Wedgewood's, Daniell's (which in principle resembled the apparatus in fig. 222), Brongniart's, etc., are gone entirely out of use. None of them gives an exact measure of temperature. The arrangements now used for the purpose are either based on the expansion of gases and vapours, or on the electrical properties of bodies, and will be subsequently described.

282. **Different remarkable temperatures.**—The following table gives some of the most remarkable points of temperature. It may be observed that it is easier to produce very elevated temperatures than very low degrees of cold.

Greatest artificial cold produced by a bath of bisulphide of carbon and liquid nitrous acid	–140° C.
Greatest cold produced by ether and liquid carbonic acid .	–110
Greatest natural cold recorded in Arctic expeditions .	– 49
Mercury freezes	– 39·4
Mixture of snow and salt	– 20

Ice melts		0
Greatest density of water		+4
Mean temperature of London		9·9
Blood heat		36·6
Water boils		100
Mercury boils		350
Red heat (just visible)	(Daniell)	526
Silver melts	„	1000
Cast iron melts	„	1530
Highest heat of wind furnace	„	1800

CHAPTER II.

EXPANSION OF SOLIDS.

283. **Linear expansion and cubical expansion. Coefficients of expansion.**—It has been already explained that in solid bodies the expansion may be according to three dimensions—linear, superficial, and cubical.

The *coefficient of linear expansion* is the elongation of the unit of length of a body when its temperature rises from zero to 1 degree; the *coefficient of superficial expansion* is the increase of the surface in being heated from zero to 1 degree, and the *coefficient of cubical expansion* is the increase of the unit of volume under the same circumstances.

These coefficients vary with different bodies, but for the same body *the coefficient of cubical expansion three times that of the linear expansion*, as is seen from the following considerations. Suppose a cube, the length of whose side is 1 at zero. Let k be the elongation of this side in passing from zero to 1 degree, its length at 1 degree will be $1+k$, and the volume of the cube, which was 1 at zero, will be $(1+k)^3$, or $1+3k+3k^2+k^3$. But as the elongation k is always a very small fraction (see table, art 285), its square k^2, and its cube k^3, are so small that they may be neglected, and the value at 1 degree becomes very nearly $1+3k$. Consequently the increase of volume is $3k$, or thrice the coefficient of linear expansion.

In the same manner it may be shown that the coefficient of superficial expansion is double the coefficient of linear expansion.

284. **Measurement of the coefficients of linear expansion. Lavoisier and Laplace's method.**—The apparatus used by Lavoisier and Laplace for determining the coefficients of linear expansion (fig. 235) consists of a copper trough, placed on a furnace between four stone supports. On the two supports, on the right hand, there is a horizontal axis, at the end of which is a telescope; on the middle of this axis, and at right angles to it, is fixed a glass rod, turning with it, as does also the telescope. The other two supports are joined by a cross piece of iron, to which another glass rod is fixed, also at right angles. The trough, which contains oil or water, is heated by a furnace not represented in the figure, and the bar whose dilatation is to be determined is placed in it.

Fig. 236 represents a section of the apparatus: G is the telescope, KH the bar, whose ends press against the two glass rods F and D. As the

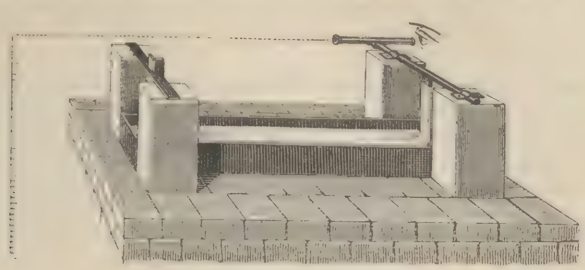


Fig. 235.

rod F is fixed, the bar can only expand in the direction KH, and in order to eliminate the effects of friction it rests on two glass rollers.

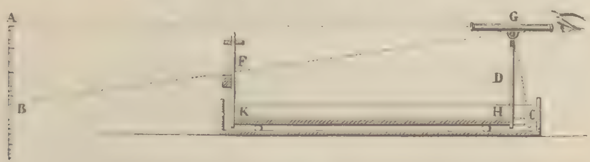


Fig. 236.

Lastly, the telescope has a cross-view in the eyepiece, which, when the telescope moves, indicates the depression by a corresponding number of divisions on a vertical scale, AB, at a distance of 220 yards.

The trough is first filled with ice, and the bar being at zero, the division on the scale AB, corresponding to the wire of the telescope, is read off. The ice having been removed, the trough is filled with oil or water, which is heated to a given temperature. The bar then expands, and when its temperature has become stationary, which is determined by means of thermometers, the division of the scale, seen through the telescope, is read off.

From these data the elongation of the bar is determined; for since it has become longer by a quantity, CH, and the optical axis of the telescope has become inclined in the direction GB, the two triangles, GHC and ABG, are similar, for they have the sides at right angles each to each, so that $\frac{HC}{AB} = \frac{GH}{AG}$. In the same way, if HC′ were another elongation, and AB′ a corresponding deviation, there would still be $\frac{HC'}{AB'} = \frac{GH}{AG}$; from which it follows that the ratio between the elongation of the bar and the deflection of the telescope is constant, for it is always equal to $\frac{GH}{AG}$. A preliminary measurement had shown that this ratio was $\frac{1}{744}$. Consequently $\frac{HC}{AB} = \frac{1}{744}$, whence $HC = \frac{AB}{744}$; that is, the total elongation of

the bar is obtained by dividing the length on the scale traversed by the cross wire by 744. Dividing this elongation by the length of the bar, and then by the temperature of the bath, the quotient is the dilatation for the unit of length and for a single degree—in other words, the coefficient of linear dilatation.

285. **Roy and Ramsden's method.**—Lavoisier and Laplace's method is founded on an artifice which is frequently adopted in physical determinations, and which consists in amplifying by a known amount dimensions which, in themselves, are too small to be easily measured. Unfortunately this plan is often more fallacious than profitable, for it is first necessary to determine the ratio of the motion measured to that on which it depends. In the present case it is necessary to know the lengths of

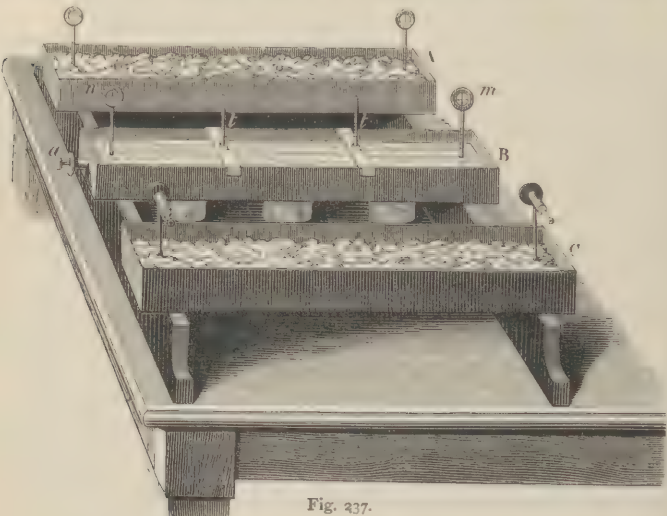


Fig. 237.

the arms of the level in the apparatus. But this preliminary operation may introduce errors of such importance as partially to counterbalance the advantage of great delicacy. The following method, which was used by General Roy in 1787, and which was devised by Ramsden, depends on another principle. It measures the elongations directly, and without amplifying them, but it measures them by means of a micrometer, which indicates very small displacements.

The apparatus (fig. 237) consists of three parallel metal troughs about 6 feet long. In the middle one there is a bar of the body whose expansion is to be determined, and in the two others are cast-iron bars of exactly the same length as this bar. Rods are fixed vertically on both sides of these three bars. On the rods in the troughs A and B there are rings with cross-wires like those of a telescope. On the rods in the trough C are small telescopes also provided with cross-wires.

The troughs being filled with ice, and all three bars at zero, the points of intersection of the wires in the disc, and of the wires in the telescope, are all in a line at each end of the bar. The temperature in the middle trough is then raised to 100° C. by means of spirit lamps placed beneath the trough; the bar expands, but as it is in contact with the end of a screw, *a*, fixed on the side, all the elongation takes place in the direction *nm*, and as the cross-wire *n* remains in position, the cross-wire *m* is moved towards B by a quantity equal to the elongation. But since the screw *a* is attached to the bar, by turning it slowly from right to left, the bar is moved in the direction *mn*, and the cross-wire *m* regains its original position. To effect this, the screw has been turned by a quantity exactly equal to the elongation of the bar, and as this advance of the screw is readily deduced from the number of turns of its *thread*, the total expansion of the bar is obtained, which, divided by the temperature of the bath, and this quotient by the length of the bar at zero, gives the coefficient of linear expansion.

Coefficients of linear expansion for 1° *between* 0° *and* 100° *C.*

White glass	0·000008613	Copper	0·000017182
Platinum	0·000008842	Bronze	0·000018167
Untempered steel	0·000010788	Brass	0·000018782
Cast iron	0·000011250	Silver	0·000019097
Wrought iron	0·000012204	Tin	0·000021730
Tempered steel	0·000012395	Lead	0·000028575
Gold	0·000014660	Zinc	0·000029417

From what has been said about the linear dilatation (283), the coefficients of cubical expansion of solids are obtained by multiplying those of linear expansion by three.

The coefficients of the expansion of the metals vary with their physical condition, being different for the same metal according as it has been cast, hammered and rolled, hardened or annealed. As a general rule, operations which increase its density increase also the rate of expansion. But even for substances in apparently the same condition, different observers have found very unequal amounts of expansions; this may arise in the case of compound substances, such as glass, brass, or steel, from a want of uniformity in chemical composition, and in simple bodies from slight differences of physical state.

The expansion of amorphous solids, and of those which crystallise in the regular system, is the same for all dimensions, unless they are subject to a strain in some particular direction. A fragment of such a substance varies in bulk, but retains the same shape. Crystals not belonging to the regular system exhibit when heated an unequal expansion in the direction of their different axes, in consequence of which the magnitude of their angles, and therefore their form, is altered. In the dimetric system the expansion is the same in the direction of the two equal axes, but different in the third. In crystals belonging to the hexagonal system the expansion is the same in the direction of the three secondary axes;

but different from that according to the principal one. In the trimetric system it is different in all three directions.

286. **The coefficients of expansion increase with the temperature.**—According to Dr. Matthiessen, who determined the expansion of the metals and alloys by weighing them in water at different temperatures, the coefficients of expansion are not quite regular between 0° and 100°. He found the following values for the linear expansion between 0° and 100°:

Zinc . . .	$L_t = L_0 (1 + 0{\cdot}00002741\ t + 0{\cdot}0000000235\ t^2)$
Lead . .	$L_t = L_0 (1 + 0{\cdot}00002726\ t + 0{\cdot}0000000074\ t^2)$
Silver . .	$L_t = L_0 (1 + 0{\cdot}00001809\ t + 0{\cdot}0000000135\ t^2)$
Copper . .	$L_t = L_0 (1 + 0{\cdot}00001408\ t + 0{\cdot}0000000264\ t^2)$
Gold . .	$L_t = L_0 (1 + 0{\cdot}00001358\ t + 0{\cdot}0000000112\ t^2)$

The same authority has found that alloys expand very nearly according to the following law : 'the coefficients of expansion of an alloy are equal to the mean of the coefficients of expansion of the volumes of the metals composing it.'

287. **Formulæ relative to the expansion of solids.**—Let l be the length of a bar at zero, l' its length at the temperature $t°$ C., and α its coefficient of linear expansion. The tables usually give the expansion for 1° between 0° and 100°, as in article 285, or for 100° ; in this latter case α is obtained by dividing the number by 100.

The relation existing between the above quantities is expressed by a few simple formulæ.

The elongation corresponding to $t°$ is t times α or αt for a single unit of length, or $\alpha t l$ for l units. The length of the bar which is l at zero is $l + \alpha t l$ at $t°$, consequently,

$$l' = l + \alpha t l = l(1 + \alpha t)$$

This formula gives the length of a body l' at $t°$, knowing its length l at zero, and the coefficient of expansion α ; and by simple algebraical transformations, we can obtain from it formulæ for the length at zero, knowing the length l' at $t°$, and also for finding α the coefficient of linear expansion, knowing the lengths l' and l at $t°$ and zero respectively.

It is obvious that the formulæ for cubical expansion are entirely analogous to the preceding.

The following are examples of the application of these formulæ :—

A metal bar has a length l' and $t'°$, what will be its length l at $t°$?

From the above formula we first get the length of the given bar at zero, which is $\dfrac{l'}{1 + \alpha t}$; by means of the same formula we pass from zero to $t'°$ in multiplying by $1 + \alpha t'$, which gives for the desired length the formula

$$l = \frac{l'(1 + \alpha t')}{1 + \alpha t}$$

The density of a body being d at zero, required its density d' at $t°$.

If 1 be the volume of the body at zero, and D its coefficient of cubical expansion, the volume at t will be $1 + Dt$, and as the density of a body

is in inverse ratio of the volume which the body assumes in expanding, we get the inverse proportion,

$$d' : d = 1 \quad : \quad 1 + Dt,$$

$$\frac{d'}{d} = \frac{1}{1 + Dt}; \text{ or } d' = \frac{d}{1 + Dt}$$

Consequently, when a body is heated from 0 to $t°$, its density, and therefore its weight for an equal volume, is inversely as the binomial expression, $1 + Dt$.

288. **Applications of the expansion of solids.**—In the arts we meet with numerous examples of the influence of expansion. (i.) The bars of furnaces must not be fitted tightly at their extremities, but must, at least, be free at one end, otherwise, in expanding, they would split the masonry. (ii.) In making railways a small space is left between the successive rails, for if they touched, the force of expansion would cause them to curve or would break the chairs. (iii.) Water pipes are fitted to one another by means of telescopic joints, which allow room for expansion. (iv.) If a glass is heated or cooled too rapidly it cracks; this arises from the fact that glass being a bad conductor of heat, the sides become unequally heated, and consequently unequally expanded, which causes a fracture.

When bodies have been heated to a high temperature, the force produced by their contraction on cooling is very considerable; it is equal to the force which is needed to compress or expand the material to the same extent by mechanical means. According to Barlow a bar of malleable iron a square inch in section is stretched $\frac{1}{10000}$ of its length by a weight of a ton; the same increase is experienced by about 9° C. A difference of 45° C. between the cold of winter and the heat of summer is not unfrequently experienced in this country. In that range a wrought iron bar ten inches long will vary in length by $\frac{1}{200}$ of an inch and will exert a strain, if its ends are securely fastened, of fifty tons. It has been calculated from Joule's data that the force exerted by heat in expanding a pound of iron between 0° and 100° during which it increases about $\frac{1}{290}$ of its bulk, is equal to 16,000 foot pounds; that is, it could raise a weight of 7 tons through a height of one foot.

(i.) An application of this contractile force is seen in the mode of securing the tires on wheels. The tire being made red hot, and thus considerably expanded, is placed on the circumference of the wheel and then cooled. The tire, when cold, embraces the wheel with such force as not only to secure itself on the rim, but also to press home the joints of the spokes into the felloes and nave. (ii.) Another interesting application was made in the case of a gallery at the Conservatoire des Arts et Métiers in Paris, the walls of which had begun to bulge outwards. Iron bars were passed across the building and screwed into plates on the outside of the walls. Each alternate bar was then heated by means of lamps, and when the bar had expanded it was screwed up. The bars being then allowed to cool contracted, and in so doing drew the walls together. The same operation was performed on the other bars.

289. **Compensation pendulum.**—An important application of the

expansions of metals has been made in *the compensation pendulum*. This is a pendulum in which the elongation, when the temperature rises, is so compensated that the distance between the centre of suspension and the centre of oscillation (71) remains constant, which, from the laws of the pendulum (72), is necessary for isochronous oscillations, and in order that the pendulum may be used as a regulator of clocks.

In fig. 238, which represents the *gridiron* pendulum, one of the commonest forms of compensation pendulums, the ball, L, instead of being supported by a single rod, is supported by a framework, consisting of alternate rods of steel and brass. In the figure the shaded rods represent steel ; including a small steel rod, *b*, which supports the whole of the apparatus, there are six of them. The rest of the rods, four in number, are of brass. The rod, *i*, which supports the ball, is fixed at its upper end to a horizontal cross-piece ; at its lower end it is free, and passes through the two circular holes in the lower horizontal cross-pieces.

Now it is easy to see from the manner in which the vertical rods are fixed to the cross-pieces, that the elongation of the steel rods can only take place in a downward direction, and that of the brass rods in an upward direction. Consequently, in order that the pendulum may remain of the same length, it is necessary that the elongation of the brass rods shall tend to make the ball rise by exactly the same quantity that the elongation of the steel rod tends to lower it : a result which is attained when the sum of the lengths of the steel rods A is to the sum of the lengths of the brass rods B in the inverse ratio of the coefficients of expansion of steel and brass, a and b, that is, in the proportion $A : B = b : a$.

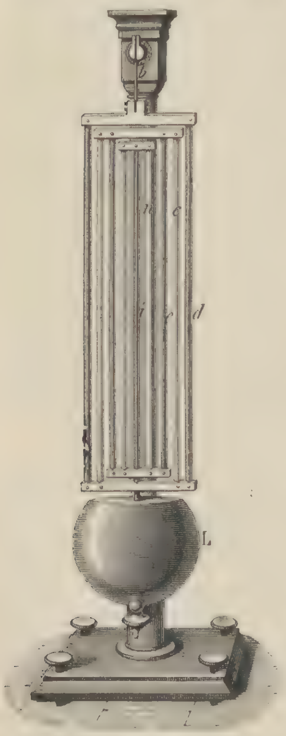


Fig. 238.

The elongation of the rod may also be compensated for by means of *compensating strips*. These consist of two blades of copper and iron soldered together and fixed to the pendulum rod, as represented in fig. 239. The copper blade, which is more expansible, is below the iron. When the temperature sinks, the pendulum rod becomes shorter, and the ball rises. But at the same time the compensating strips become curved, as seen in fig. 240, in consequence of the copper contracting more than the iron, and two metallic balls at their extremities become lower. If they have the proper size in reference to the pendulum ball, the parts which

tend to approach the centre of suspension compensate those which tend to remove from it, and the centre of oscillation is not displaced. If the temperature rises the pendulum ball descends, but at the same time the small balls ascend, as shown in fig. 241, so that there is always compensation.

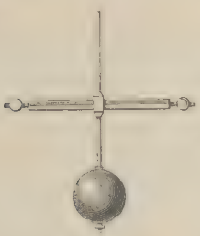


Fig. 239.

Fig. 240.

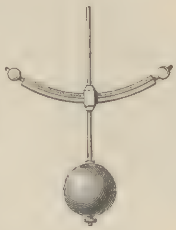


Fig. 241.

One of the most simple compensating pendulums is the *mercury pendulum*, invented by an English watchmaker, Graham. The ball of the pendulum, instead of being solid, consists of a glass cylinder, containing pure mercury, which is placed in a sort of stirrup, supported by a steel rod. When the temperature rises the rod and stirrup become longer, and thus lower the centre of gravity; but at the same time the mercury expands, and, rising in the cylinder, produces an inverse effect, and as mercury is much more expansible than steel, a compensation may be effected without making the mercurial vessel of undue dimensions.

The same principle is applied in the *compensating balances* of chronometers. The motion here is regulated by a *balance* or wheel, furnished with a spiral spring, and the time of the chronometer depends on the force of the spring, the mass of the balance, and on its circumference. Now when the temperature rises the circumference increases, and the chronometer goes slower; and to prevent this, part of the mass must be brought nearer the axis. On the circumference of the balance compensating strips are fixed, of which the more expansible metal is on the outside, and at the end of these are small masses of metal which play the same part as the balls in the above case. When the radius is expanded by heat, the small masses are brought nearer the centre in consequence of the curvature of the strips; and as they can be fixed in any position, they are easily arranged so as to compensate for the expansion of the balance.

CHAPTER III.

EXPANSION OF LIQUIDS.

290. **Apparent and real expansion.**—If a flask of thin glass, provided with a capillary stem, the flask and part of the stem being filled with some coloured liquid, be immersed in hot water, the column of liquid in

the stem at first sinks, but then immediately after rises, and continues to do so until the liquid inside has the same temperature as the hot water. This first sinking of the liquid is not due to its contraction; it arises from the expansion of the glass, which becomes heated before the heat can reach the liquid; but the expansion of the liquid soon exceeds that of the glass, and the liquid ascends.

Hence in the case of liquids we must distinguish between the *apparent* and the *real* or *absolute* expansion. The apparent expansion is that which is actually observed when liquids contained in vessels are heated: the *absolute* expansion is that which would be observed if the vessel did not expand; or, as this is never the case, is the apparent expansion corrected for the simultaneous expansion of the containing vessel.

As has been already stated, the cubical expansion of liquids is alone considered; and as in the case of solids, the *coefficient of expansion* of a liquid is the increase of the unit of volume for a single degree, but a distinction is here made between the *coefficient of absolute expansion* and the *coefficient of apparent expansion.* Of the many methods which have been employed for determining these two coefficients, we shall describe that of Dulong and Petit.

291. **Coefficient of the absolute expansion of mercury.**—In order to determine the coefficient of absolute expansion of mercury, the influence of the envelope must be eliminated. Dulong and Petit's method depends on the hydrostatical principle that, in two communicating vessels, the heights of two columns of liquid in equilibrium are inversely as their densities (99), a principle independent of the diameters of the vessels and therefore of their expansions.

The apparatus consists of two glass tubes, A and B (fig. 242), joined by a capillary tube, and kept vertical on an iron support, KM, the horizontality of which is adjusted by means of two levelling screws and two spirit levels, m and n. Each of the tubes is surrounded by a metal case, of which the smaller, D, is filled with ice; the other, E, containing oil, can be heated by the furnace, which is represented in section so as to show the case. Mercury is poured into the tubes A and B; it remains at the same level in both as long as they are at the same temperature, but rises in B in proportion as it is heated, and expands.

Let h and d be the height and density of the mercury in the leg A, at the temperate zero, and h' and d' the same quantities in the leg B. From the hydrostatical principle previously cited we have had $hd = h'd'$. Now from the problem in article 287, $d' = \frac{d}{1 + Dt}$, D being the coefficient of absolute expansion of mercury; substituting this value of d' in the equation we have $\frac{h'd}{1 + Dt} = hd$, from which we get $D = \frac{h' - h}{ht}$.

The coefficient of absolute expansion of mercury is obtained from this formula, knowing the heights h' and h, and the temperature t of the bath in which the tube B is immersed. In Dulong and Petit's experiment this temperature was measured by a weight thermometer, P (293), the mercury of which overflowed into the basin, C, and by means of an air

thermometer, T (302); the heights h' and h were measured by a cathetometer, K (80).

Dulong and Petit found by this method that the coefficient of absolute expansion of mercury, between 0° and 100° C. is $\frac{1}{5550}$. But they found

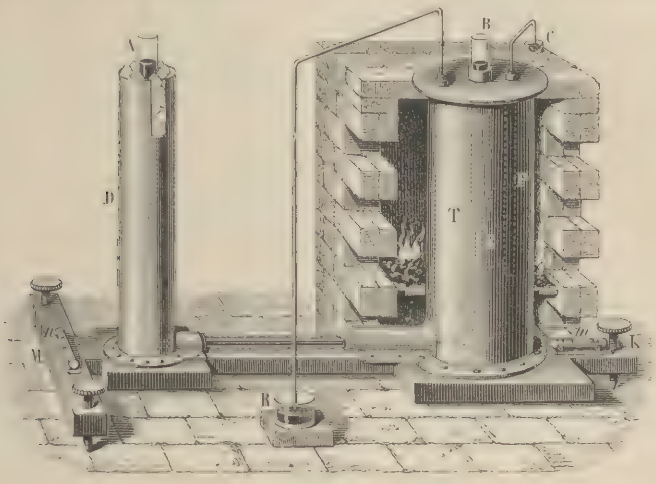


Fig. 242.

that the coefficient increased with the temperature. Between 100° and 200° it is $\frac{1}{5425}$, and between 200° and 300° it is $\frac{1}{5300}$. The same observation has been made in reference to other liquids, showing that their expansion is not regular. It has been found that this expansion is less regular in proportion as liquids are near a change in their state of aggregation, that is, approach their freezing or boiling points. Dulong and Petit found that the expansion of mercury between − 36° and 100° is practically quite uniform.

Regnault, who has determined this important physical constant, has found that the mean coefficient between 0° and 100° is $\frac{1}{5508}$, between 100° and 200, $\frac{1}{5374}$, and between 200 and 300°, $\frac{1}{5218}$.

292. **Coefficient of the apparent expansion of mercury.**—The coefficient of apparent expansion of a liquid varies with the nature of the envelope. That of mercury in glass was determined by means of the apparatus represented in figure 243. It consists of a glass cylinder to which is joined a bent capillary glass tube, open at the end.

Fig. 243.

The apparatus is weighed first empty, and then when filled with mercury at zero; the difference gives the weight of the mercury, P. It is

then raised to a known temperature, t; the mercury expands, a certain quantity passes out, which is received in the capsule and weighed. If the weight of this mercury be p, that of the mercury remaining in the apparatus will be $P-p$.

When the temperature is again zero, the mercury in cooling produces an empty space in the vessel, which represents the contraction of the weight of mercury $P-p$, from $t°$ to zero, or, what is the same thing, the expansion of the same weight from o to $t°$, that is, the weight p represents the expansion of the weight $P-p$, for $t°$. If this weight expands in glass by a quantity p for $t°$, a single unit of weight would expand $\frac{p}{(P-p)}$ for $t°$ and $\frac{p}{(P-p)t}$ for a single degree; consequently, for D′, the coefficient of apparent expansion of mercury in glass we have $D' = \frac{p}{(P-p)t}$. Dulong and Petit found the coefficient of apparent expansion of mercury in glass to be $\frac{1}{6480}$.

293. **Weight thermometer.**—The apparatus represented in fig. 243 is called the *weight thermometer*, because the temperature can be deduced from the weight of mercury which overflows.

The above experiments have placed the coefficient of apparent expansion at $\frac{1}{6480}$; we have therefore the equation $\frac{p}{(P-p)t} = \frac{1}{6480}$, from which we get $t = \frac{6480p}{P-p}$, a formula which gives the temperature t when the weight P and p are known.

294. **Coefficient of the expansion of glass.**—As the absolute expansion of a liquid is the apparent expansion plus the expansion due to the envelope, the coefficient of the cubical expansion of glass has been obtained by taking the difference between the coefficient of absolute expansion of mercury in glass, and that of its apparent expansion. That is, the coefficient of cubical expansion of glass is

$$\frac{1}{5508} - \frac{1}{6480} = \frac{1}{38700} = 0{\cdot}002584.$$

Regnault has found that the coefficient of expansion varies with different kinds of glass, and further with the form of the envelopes. For ordinary chemical glass tubes, the coefficient is 0·0000254.

295. **Coefficients of expansion of various liquids.**—The apparent expansion of liquids may be determined by means of the weight thermometer, and the absolute expansion is obtained by adding to this coefficient the expansion of the glass.

Total apparent expansions of liquids between 0° *and* 100° *C.*

Mercury	0·01543	Oil of turpentine	0·07
Distilled water	0·0466	Ether	0·07
Water saturated with salt	0·05	Fixed oils	0·08
Sulphuric acid	0·06	Nitric acid	0·11
Hydrochloric acid	0·06	Alcohol	0·116

The coefficient of apparent expansion for 1° C. is obtained by dividing

these numbers by 100; but the number thus obtained does not represent the mean coefficient of expansion of liquids, for the expansion of these bodies increases gradually from zero. The expansion of mercury is practically constant between $-36°$ and $100°$ C., while water contracts from zero to $4°$, and then expands.

For many physical experiments a knowledge of the exact expansion of water is of great importance. This physical constant has been determined with great care by Dr. Matthiessen, who has found that between $4°$ and $32°$ it may be expressed by the formula

$$Vt = 1 - 0{\cdot}00000253\,(t-4) + 0{\cdot}0000008389\,(t-4)^2 + 0{\cdot}00000007173\,(t-4)^3$$

and between $30°$ and $100°$ by

$$Vt = 0{\cdot}999695 + 0{\cdot}0000054724\,t^2 + 0{\cdot}00000001126\,t^3$$

Many liquids, with low boiling points, especially condensed gases, have very high coefficients of expansion. Thilorier found that liquid carbonic acid expands four times as much as air. Drion has recently confirmed this observation, and has obtained analogous results with chloride of ethyle, liquid sulphurous acid, and liquid hyponitrous acid.

296. **Correction of the barometric height.**—It has been already explained under the Barometer (156), that, in order to make the indications of this instrument comparable in different places and at different times, they must be reduced to a uniform temperature, which is that of melting ice. The correction is made in the following manner :

Let H be the barometric height at $t°$, and h its height at zero, d the density of mercury at zero, and d' its density at $t°$. The heights H and h are inversely as the densities d and d'; that is, $\frac{h}{H} = \frac{d'}{d}$. If we call 1 the volume of mercury at zero, its volume at $t°$ will be $1 + Dt$, D, being the coefficient of absolute expansion of mercury. But these volumes, $1 + Dt$ and 1, are inversely as the densities d and d'; that is, $\frac{d'}{d} = \frac{1}{1 + Dt}$. Consequently, $\frac{h}{H} = \frac{1}{1 + Dt}$, whence $h = \frac{H}{1 + Dt}$. Replacing D by its value $\frac{1}{5508}$, we have $h = \dfrac{H}{1 + \dfrac{t}{5508}} = \dfrac{5508H}{5508 + t}$.

In this calculation, the coefficient of absolute expansion of mercury is taken and not that of apparent expansion : for the value H is the same as if the glass did not expand, the barometric height being independent of the diameter of the tube, and therefore of its expansion.

297. **Force exerted by liquids in expanding.**—The force which liquids exert in expanding is very great, and equal to that which would be required in order to bring the expanded liquid back to its original volume. Now we know what an enormous force is required to compress a liquid to even a very small extent. Thus between $0°$ and $10°$, mercury expands by $0{\cdot}0017905$ of its volume at $0°$; its compressibility is $0{\cdot}00000295$ of its volume for one atmosphere ; hence a pressure of more than 600 atmospheres would be requisite to prevent mercury expanding when heated from $0°$ to $10°$.

298. **Maximum density of water.**—Water presents the remarkable phenomenon that when its temperature sinks it contracts up to 4°; but from that point, although the cooling continues, it expands up to the freezing point, so that 4° represent the point of greatest contraction of water.

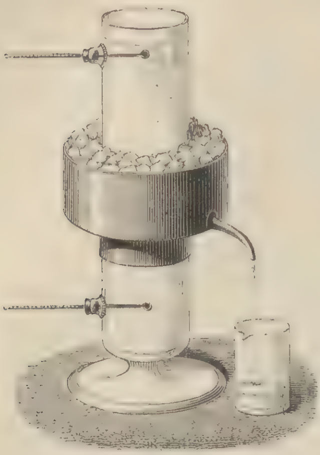


Fig. 244.

Many methods have been used to determine the maximum density of water. Hope made the following experiment. He took a deep vessel, perforated by two lateral apertures, in which he fixed thermometers, and having filled the vessel with water at 0°, he placed it in a room at a temperature of 15°. As the layers of liquid at the sides of the vessel became heated they sank to the bottom, and the lower thermometer marked 4°, while that of the upper one was still at zero. Hope then made the inverse experiment: having filled the vessel with water at 15°, he placed it in a room at zero. The lower thermometer having sunk to 4°, remained stationary for some time, while the upper one cooled down until it reached zero. Both these experiments prove that water is heavier at 4° than at 0°, for in both cases it sinks to the lower part of the vessel.

This last experiment may be adapted for lecture illustrations by using a cylinder containing water at 15° C., surrounded with a sheath containing bruised ice (fig. 244).

Hallström made a determination of the maximum density of water in the following manner. He took a glass bulb, loaded with sand, and weighed it in water of different temperatures. Allowing for the expansion of glass, he found that 4·1° was the temperature at which it lost most weight, and consequently this was the temperature of the maximum density of water.

Despretz arrived at the temperature 4° by another method. He took a water thermometer, that is to say, a bulbed tube containing water, and placing it in a bath, the temperature of which was indicated by an ordinary mercury thermometer, found that the water contracted to the greatest extent at 4°, and that this is therefore the point of greatest density.

This phenomenon is of great importance in the economy of nature. In winter the temperature of lakes and rivers falls from being in contact with the cold air, and from other causes, such as radiation. The colder water sinks to the bottom, and a continual series of currents goes on until the whole has a temperature of 4°. The cooling on the surface still continues, but the cooled layers being lighter remain on the surface, and ultimately freeze. The ice formed thus protects the water below,

which remains at a temperature of 4°, even in the most severe winters, a temperature at which fishes and other inhabitants of the waters are not destroyed.

CHAPTER IV.

EXPANSION AND DENSITY OF GASES.

299. **Gay-Lussac's method.**—Gases are the most expansible of all bodies, and at the same time the most regular in their expansion. The coefficients of expansion, too, of the several gases, differ only by very small quantities. The cubical expansion of gases need alone be considered.

Gay-Lussac first determined the coefficient of the expansion of gases by means of the apparatus represented in fig. 245.

In a rectangular metal bath, about 16 inches long, was fitted an air thermometer, which consisted of a capillary tube, AB, with a bulb, A,

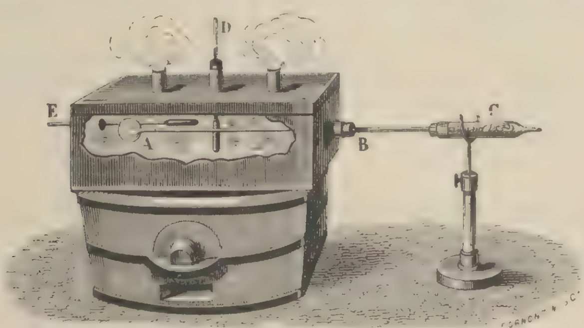


Fig. 245.

at one end. The tube was divided into parts of equal capacity, and the contents of the bulb ascertained in terms of these parts. This was effected by weighing the bulb and tube full of mercury at zero, and then heating slightly to expel a small quantity of mercury, which was weighed. The apparatus being again cooled down to zero, the vacant space in the tube corresponded to the weight of mercury which had overflowed; the volume of mercury remaining in the apparatus, and consequently the volume of the bulb, was determined by calculations analogous to those made for the piezometer (89).

In order to fill the thermometer with dry air it was first filled with mercury, which was boiled in the bulb itself. A tube, C, filled with chloride of calcium, was then fixed on to its end by means of a cork. A fine platinum wire having then been introduced into the stem AB, through the tube C, and the apparatus being slightly inclined and agitated from time to time, air entered, having been previously well dried by passing through the chloride of calcium tube. The whole of the mercury was

displaced with the exception of a small thread, which remained in the tube AB as an index.

The air thermometer was then placed in the box filled with melting ice, the index moved towards A, and the point was noted at which it became stationary. This gave the volume of air at zero; for the capacity of the bulb was known. Water or oil was then substituted for the ice, and the bath successively heated to different temperatures. The air expanded and moved the index from A towards B. The position of the index in each case was noted, and the corresponding temperature was indicated by means of the thermometers D and E.

Assuming that the atmospheric pressure did not vary during the experiment, and neglecting the expansion of the glass as being too small in comparison with that of the air, the total expansion of the air is obtained by subtracting from its volume at a given temperature its volume at zero. Dividing this by the given temperature, and then by the number of units contained in the volume at zero, the quotient is the coefficient of expansion for a single unit of volume and a single degree; that is, the *coefficient of expansion.* It will be seen, further on, how corrections for pressure and temperature may be introduced.

By this method Gay-Lussac found that the co-efficient of expansion of air was 0·00375; and he enunciated the two following laws in reference to the expansion of gases:

I. *All gases have the same coefficient of expansion as air.*

II. *This coefficient is the same whatever be the pressure supported by the gas.*

These simple laws are not, however, rigorously exact (301); they only express the expansion of gases in an approximate manner.

300. **Problems on the expansion of gases.**—Many of the problems relative to the expansion of gases are similar to those on the expansion of liquids. With obvious modifications they are solved in a similar manner. In most cases, the pressure of the atmosphere must be taken into account in considering the expansion of gases. The following is an example of the manner in which this correction is made:

i. The volume of a gas at $t°$, and under the pressure H, is V′; what will be the volume V of the same gas at zero, and under the normal pressure 760 millimeters?

Here there are two corrections to be made; one relative to the temperature, and the other to the pressure. It is quite immaterial which is taken first. If α be the coefficient of cubical expansion for a single degree, by reasoning similar to that in the case of linear expansion (283), the volume of the gas at zero, but still under the pressure H, will be $\frac{V'}{1+\alpha t}$. This pressure is reduced to the pressure 760, in accordance with Boyle's law (163), by putting

$$V \times 760 = \frac{V'}{1+\alpha t} \times H$$

whence

$$V = \frac{V'H}{760\,(1+\alpha t)}$$

ii. A volume of gas weighs P′ at $t°$; what will be its weight at zero?

Let P be the desired weight, α the coefficient of expansion of the gas, d' its density at $t°$, and d its density at zero. As the weights of equal volumes are proportional to the densities, we have $\frac{P'}{P} = \frac{d'}{d}$. If 1 be the volume of a gas at zero, its volume at t will be $1 + \alpha t$; but as the densities are inversely as the volumes $\frac{d'}{d} = \frac{1}{1 + \alpha t}$, and therefore

$$\frac{P'}{P} = \frac{1}{1 + \alpha t}$$

whence

$$P = P'(1 + \alpha t)$$

From this equation we get $P' = \frac{P}{1 + \alpha t}$, which gives the weight at t, knowing the weight at zero, and which further shows that the weight P′ is inversely as the binomial of expansion $1 + \alpha t$.

301. **Regnault's method.**—M. Regnault used successively four different methods for determining the expansion of gases. In some of them, the pressure was constant and the volume variable, as in Gay-Lussac's method; in others the volume remained the same while the pressure varied. The first method will be described. It is the same as that used by Rudberg and Dulong, but is distinguished by the care with which all sources of error are avoided.

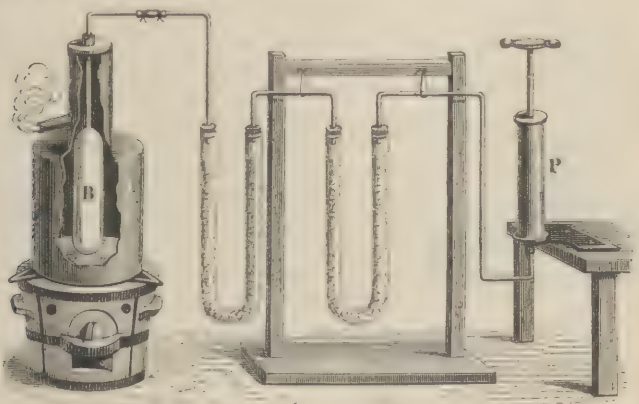


Fig. 246.

The apparatus consisted of a pretty large cylindrical reservoir, B (fig. 246), terminating in a bent capillary tube. In order to fill the reservoir with dry air, it was placed in a hot water bath, and the capillary tube connected by a caoutchouc tube with a series of drying tubes. These tubes were joined to a small air pump, P, by which a vacuum could be produced in the reservoir while at a temperature of 100°. The reservoir was first exhausted, and air afterwards admitted slowly: this operation

was repeated a great many times, so that the air in the reservoir became quite dry, for the moisture adhering to the sides passed off in vapour at 100°, and the air which entered became dry in its passage through the U tubes.

The reservoir was then kept for half an hour at the temperature of boiling water; the air pump having been detached, the drying tubes were then disconnected, and the end of the tube hermetically sealed, the height, H, of the barometer being noted. When the reservoir B was cool, it was placed in the apparatus represented in fig. 247. It was there quite surrounded with ice, and the end of the tube dipped in the mercury bath, C. After the air in the reservoir B had sunk to zero, the point *b* was broken off by means of a forceps; the air in the interior became condensed by atmospheric pressure, the mercury rising to a height *o*G. In order to measure the height of this column, G*o*, which will be called *h*, a movable rod, *go*, was lowered until its point, *o*, was flush with the surface of the mercury in the bath; the distance between the point *o* and the level of the mercury G was measured by means of the cathetometer. The point *b* was finally closed with wax by means of the spoon *a*, and the barometric pressure noted at this moment. If this pressure be H′, the pressure in the reservoir is H′ − *h*.

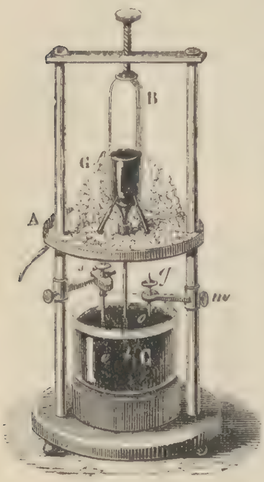


Fig. 247.

The reservoir was now weighed to ascertain P, the weight of the mercury which it contained. It was then completely filled with mercury at zero, in order to have the weight P′ of the mercury in the reservoir and in the tube.

If δ be the coefficient of the cubical expansion of glass, and D the density of mercury at zero, the coefficient α of the cubical expansion of air is determined in the following manner. The volume of the reservoir and of the tube at zero is $\frac{P'}{D}$, from the formula P = VD (117); consequently, this volume is

$$\frac{P'}{D}(1+\delta t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

at the temperature $t°$, assuming, as is the case, that the reservoir and tube expand as if they were solid glass. But from the formula P = VD, the volume of air in the reservoir at zero, and under the pressure H′ − *h*, is $\frac{P'-P}{D}$. At the same pressure, but at $t°$, its volume would be

$$\frac{P'-P}{D}(1+\alpha t)$$

and, by Boyle's law (163), at the pressure H, under which the tube was sealed, this volume must have been

$$\frac{(P'-P)\,(1+\alpha t)\,(H'-h)}{DH} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Now the volumes represented by these formulas, (1) and (2), are each equal to the volume of the reservoir and the tube at $t°$; they are therefore equal. Removing the denominators, we have

$$P'\,(1+\delta t)\,H = (P'-P)\,(1+\alpha t)\,(H'-h) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

from which the value of α is deduced.

The means of a great number of experiments between zero and 100°, and for pressures between 300 millimeters and 500 millimeters, gave the following numbers for the coefficients of expansion for a single degree.

Air	0·0036650	Hydrochloric acid . .	0·0036812
Hydrogen	0·0036678	Cyanogen	0·0036821
Nitrogen	0·0036682	Carbonic acid . . .	0·0036896
Sulphurous acid . . .	0·0036606		

These numbers, with which the results obtained by Magnus closely agree, show that the coefficients of expansion of the permanent gases differ very little; but that they are slightly greater in the case of the condensible gases, such as carbonic and sulphurous acids. Regnault has further found, that, at the same temperature, the coefficient of expansion of any gas increases with the pressure which it supports. Finally he has found that the coefficients of expansion of two different gases differ more in proportion as they are under greater pressures.

The number found by Regnault for the cofficient of the expansion of air, 0·003665, is equal to $\frac{1}{272·9} = \frac{1}{273}$ nearly; and if we take the coefficient of expansion at 0·0036666 . . . it may be represented by the fraction $\frac{11}{3000}$, which is very convenient for purposes of calculation.

302. **Air thermometer.**—The *air thermometer* is based on the expansion of air. When it is used to measure small differences of temperature, it has the same form as the tube used by Gay-Lussac in determining the expansion of air (fig. 245), that is, a capillary tube with a bulb at the end. The reservoir being filled with dry air, an index of coloured sulphuric acid is passed into the tube; the apparatus is then graduated in Centigrade degrees by comparing the positions of the index with the indications of a mercurial thermometer. Of course the end of the tube must remain open: otherwise, the air above the index condensing or expanding at the same time as that in the bulb, the index would remain stationary. A correction must be made at each observation for the atmospheric pressure.

When considerable variations of temperature are to be measured, the tube has a form like that used in Regnault's experiments (fig. 246, and

247). By experiments made as described in paragraph 283, P, P′, H, H′, and h, may be found, and the coefficients α and δ being known, the temperature t to which the tube has been raised is readily deduced from the equation (3).

Regnault's researches show that the air and the mercurial thermometer agree up to 260°, but above that point mercury expands relatively more than air.

In cases where very high temperatures are to be measured the reservoir is made of platinum. The use of an air thermometer is seen in Dulong and Petit's experiment (291); it was by such an apparatus that Pouillet measured the temperature corresponding to the colours which metals take when heated in a fire, and found them to be as follows :—

Incipient red . . .	525°C.	Dark orange . . .	1100°C.
Dull red	700	White	1300
Cherry red . . .	900	Dazzling white . .	1500

In the measurement of high temperatures Deville and Troost have used, with advantage, the vapour of iodine instead of air.

303. **Density of gases.**—The relative *density* of a gas, or its *specific gravity*, is the ratio of the weight of a certain volume of the gas to that of the same volume of air; both the gas and the air being at zero and at a pressure of 760 millimeters.

In order, therefore, to find the specific gravity of a gas, it is necessary to determine the weight of a certain volume of this gas, at a pressure of 760 millimeters, and a temperature of zero, and then the weight of the same volume of air under the same conditions. For this purpose a large globe of about two gallons capacity is used, the neck of which is provided with a stopcock, which can be screwed to the air pump. The globe is first weighed empty, and then full of air, and afterwards full of the gas in question. The weights of the gas and of the air are obtained by subtracting the weight of the exhausted globe from the weight of the globes filled, respectively, with air and gas. The quotient, obtained by dividing the latter by the former, gives the specific gravity of the gas. It is difficult to make these determinations at the same temperature and pressure, and therefore all the weights are reduced to zero and the normal pressure of 760 millimeters.

The gases are dried by causing them to pass through drying tubes before they enter the globe, and air must also be passed over potash to free it from carbonic acid. And as even the best air pumps never produce a perfect vacuum, it is necessary to exhaust the globe until the manometer in each case marks the same pressure.

The globe having been exhausted, dried air is allowed to enter, and the process is repeated several times until the globe is perfectly dried. It is then finally exhausted until the residual tension, in millimeters, is e. The weight of the exhausted globe is p. Air, which has been dried and purified by passing through potash and chloride of calcium tubes, is then allowed to enter slowly. The weight of the globe full of air is P. If H

is the barometric height in millimeters, and $t°$ the temperature at the time of weighing, $P-p$ is the weight of the globe full of air at the temperature t, and the pressure $H-e$.

To reduce this weight to the pressure 760 millimeters and the temperature zero, let α be the coefficient of the expansion of air, and δ the coefficient of the cubical expansion of glass. From Boyle's law the weight, which is $P-p$ at $t°$, and a pressure of $H-e$ would be $\frac{(P-p)760}{H-e}$ under the pressure 760 millimeters and at the same temperature $t°$. If the temperature is 0°, the capacity of the globe will diminish in the ratio $1+\delta t$ to 1, while the weight of the gas increases in the ratio $1 : 1+\alpha t$, as follows from the problems in art. 300. Consequently the weight of the air in the globe at 0°, and at the pressure 760 millimeters will be

$$(P-p)\frac{760\,(1+\alpha t)}{(H-e)\,(1+\delta t)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Further, let α' be the coefficient of expansion of the gas in question; let P' be the weight of the globe full of the gas at the temperature t' and the pressure H', and let p' be the weight of the globe when it is exhausted to the tension e; the weight of the gas in the globe at the pressure 760 and the temperature zero will be

$$(P'-p')\frac{760\,(1+\alpha' t')}{(H'-e)\,(1+\delta t')} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Dividing the latter formula by the former we obtain the density

$$D=\frac{(P'-p')\,(H-e)\,(1+\alpha' t')\,(1+\delta t)}{(P-p)\,(H'-e)\,(1+\alpha t)\,(1+\delta t')}$$

If the temperature and the pressure do not vary during the experiment, $H=H'$ and $t=t'$; whence $D=\frac{(P'-p')(1+\alpha' t)}{(P-p)\,(1+\alpha t)}$, and if $\alpha=\alpha'$, $D=\frac{P'-p'}{P-p}$.

304. **Regnault's method of determining the density of gases.**—M. Regnault has so modified the above method that many of the corrections may be dispensed with. The globe in which the gas is weighed is suspended from one pan of a balance, and is counterpoised by means of a second globe of the same dimensions, and hermetically sealed, suspended from the other. These two globes expanding at the same time always displace the same quantity of air, and consequently variations in the temperature and pressure of the atmosphere do not influence the weighing. The globe, too, is filled with the air or with the gas, at the temperature of zero. This is effected by placing it in a vessel full of ice, as shown in fig. 248. It is then connected with a three-way cock A, by which it may be connected either with an air pump, or with the tubes M and N, which are connected with the reservoir of gas. The

tubes M and N contain substances by which their action on the gas dry and purify it.

The stopcock A being so turned that the globe is only connected with the air pump, a vacuum is produced; by means of the same cock, the connection with the machine being cut off, but established between M

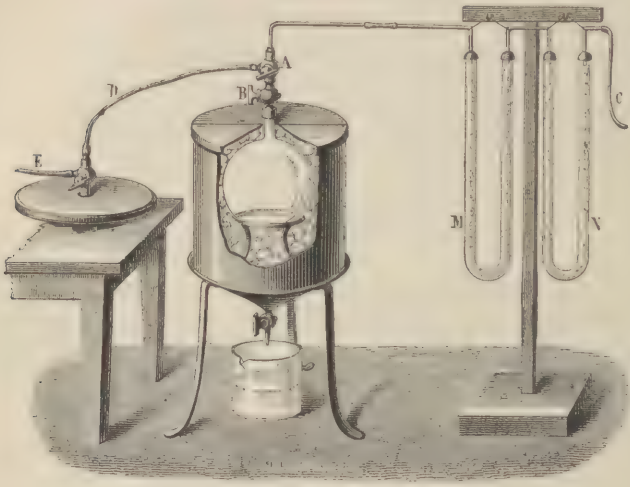


Fig. 248.

and N, the gas soon fills the globe. But as the exhaustion could not have been complete, and some air must have been left, the globe is again exhausted and the air allowed to enter, and the process repeated until it is thought all air is removed. The globe being once more produced a differential barometer (fig. 112), connected with the apparatus by the tube E, indicates the pressure of the residual rarefied gas *e*. Closing the cock B and detaching A, the globe is removed from the ice, and after being cleaned is weighed.

This gives the weight of the empty globe p; it is again replaced in the ice, the stopcock A adjusted, and the gas allowed to enter, care being taken to leave the stopcocks open long enough to allow the gas in the globe to acquire the pressure of the atmosphere, which is marked by the barometer H. The stopcock B is then closed, A removed, and the globe weighed with the same precautions as before. This gives the weight P_1 of the gas.

The same operations are then repeated on this globe with air, and two corresponding weights p and P are obtained. The only correction necessary is to reduce the weights in the two cases to the standard pressure by the method described in the preceding paragraph. The

correction for temperature is not needed, as the gas is at the temperature of melting ice. The ratio of the weight of the gas to that of the air is thus obtained by the formula

$$D = \frac{P_1 - p'}{P - p}$$

305. **Density of gases which attack metals.**—For gases which attack the ordinary metals, such as chlorine, a metal stopcock cannot be used, and vessels with ground glass stoppers are substituted. The gas is introduced by a bent glass tube, the vessel being held either upright or inverted, according as the gas is heavier or lighter than air; when the vessel is supposed to be full, the tube is withdrawn, the stopper inserted, and the weight taken. This gives the weight of the vessel and gas. If the capacity of the vessel be measured by means of water, the weight of the air which it contains is deduced, for the density of air at 0° C. and 760 millimeters pressure, is $\frac{1}{773}$ that of distilled water under the same circumstances. The weight of the vessel full of air, less the weight of the contained air, gives the weight of the vessel itself. From these three data —the weight of the vessel full of the gas, the weight of the air which it contains, and the weight of the vessel alone—the specific gravity of the gas is readily deduced, the necessary corrections being made for temperature and pressure.

Density of gases at zero and at a pressure of 760 *millimeters, that of air being taken as unity.*

Air	1·0000	Sulphuretted hydrogen	1·1912
Hydrogen	0·0693	Hydrochloric acid	1·2540
Marsh gas	0·5590	Protoxide of nitrogen	1·5270
Ammoniacal gas	0·5367	Carbonic acid	1·5291
Carbonic oxide	0.9670	Cyanogen	1·8600
Nitrogen	0·9714	Sulphurous acid	2·2474
Binoxide of nitrogen	1·0360	Chlorine	3·4400
Oxygen	1·1057	Hydriodic acid	4·4430

Regnault has furnished the following determinations of the weight of a litre of the most important gases at 0° C. and 760 mm.

Air	1·293187 grms.	Nitrogen	1·256167 grms.
Oxygen	1·429802	Carbonic acid	1·977414
Hydrogen	0·089578		

CHAPTER V.

CHANGES OF CONDITION. VAPOURS.

306. **Fusion. Its laws.**—The only phenomena of heat with which we have hitherto been engaged have been those of expansion. In the case of solids it is easy to see that this expansion is limited. For in proportion as a body absorbs a larger quantity of heat, the repulsive force between the molecules is increased, and ultimately a point is reached at which the molecular attraction is not sufficient to retain the body in the solid state. A new phenomenon is then produced; *fusion* takes place; that is, the body passes from the solid into the liquid state.

Some substances, however, such as paper, wood, wool, and certain salts, do not fuse at a high temperature, but are decomposed. Many bodies have long been considered *refractory*; that is, incapable of fusion; but, in proportion as it has been possible to produce higher temperatures, their number has diminished. Gaudin has succeeded in fusing rock crystal by means of a lamp fed by a jet of oxygen; and more recently Despretz, by combining the effects of the sun, the voltaic battery, and the oxy-hydrogen blow-pipe, has melted alumina and magnesia, and softened carbon, so as to be flexible, which is a condition near that of fusion.

It has been experimentally found that the fusion of bodies is governed by the two following laws:

I. *Every substance begins to fuse at a certain temperature, which is invariable for each substance if the pressure be constant.*

II. *Whatever be the intensity of the source of heat, from the moment fusion commences, the temperature of the body ceases to rise, and remains constant until the fusion is complete.*

Fusing points of certain substances.

Mercury	−38·8°	Sodium	90°
Bromine	−12·5°	Rose's fusible metal	94
Ice	0	Sulphur	114
Butter	+33	Tin	228
Phosphorus	44	Bismuth	264
Spermaceti	49	Cadmium	321
Potassium	55	Lead	335
Margaric acid	57	Zinc	422
Stearine	60	Antimony	450
White wax	65	Silver	1000
Wood's fusible metal	68·5	Gold	1250
Stearic acid	70	Iron	1500

Some substances pass from the solid to the liquid state without showing any definite melting point; for example, glass and iron become gradually softer and softer when heated, and pass by imperceptible stages from the solid to the liquid condition. This intermediate condition is spoken of as the state of *vitreous fusion*. Such substances may be said to melt at the lowest temperature at which perceptible softening occurs, and to be fully melted when the further elevation of temperature does not make them more fluid; but no precise temperature can be given as their melting points.

The variations which take place in the ordinary atmospheric pressure have no perceptible influence on the melting point of substances; but greater variations in pressure have a very appreciable effect. Prof. W. Thomson found that pressures of 8·1 and 16·8 atmospheres lowered the melting point of ice by 0·059° and 0·126° C. respectively. These results justify the theoretical conclusions of Prof. J. Thomson, according to which an increase of pressure of n atmospheres lowers the melting point of ice by 0·0074 n° C.

In the case of some substances, however, the melting point is increased by pressure. Thus, Hopkins has found that the melting point of wax, which at the ordinary pressure is 64·7°, is 74·7° under a pressure of 520, and 80·2 under a pressure of 793 atmospheres; the melting point of spermaceti is raised 29° by a pressure of 795 atmospheres. These results have been confirmed by Bunsen for lower pressures.

In general all those substances which *expand* on *liquefying*, such as wax, sulphur, etc., have their melting points *raised* by increased pressure: those, on the contrary, which *contract* on *liquefying*, have their melting points *lowered* by increased pressure.

307. **Alloys. Fluxes.**—Alloys are generally more fusible than either of the metals of which they are composed; for instance, an alloy of five parts of tin and one of lead fuses at 194°. The alloy known as *Rose's fusible metal*, which consists of 4 parts of bismuth, 1 part of lead, and 1 of tin, melts at 94°, and an alloy of 1 or 2 parts of cadmium with 2 parts of tin, 4 parts of lead, and 7 or 8 parts of bismuth, known as *Wood's fusible metal*, melts between 66° and 71° C. Fusible alloys are of extended use in soldering and in taking casts.

Mixtures of the fatty acids melt at lower temperatures than the pure acids. A mixture of the chlorides of potassium and of sodium fuses at a lower temperature than either of its constituents; the same is the case with a mixture of the carbonates of potassium and sodium, especially when they are mixed in the proportion of their chemical equivalents.

An application of this property is met with in the case of *fluxes* which are much used in metallurgical operations. They consist of substances which, when added to an ore, partly by their chemical action, help the reduction of the substance to the metallic state, and, partly by presenting a readily fusible medium, promote the formation of a regulus.

308. **Latent heat.**—Since, during the passage of a body from the solid to the liquid state, the temperature remains constant until the fusion is

complete, whatever be the intensity of the source of heat, it must be concluded that, in changing their condition, bodies absorb a considerable amount of heat, the only effect of which is to maintain them in the liquid state. This heat, which is not indicated by the thermometer, is called *latent heat*, or *latent heat of fusion*, an expression which, though not in strict accordance with modern ideas, is convenient from the fact of its universal recognition and employment.

An idea of what is meant by latent heat may be obtained from the following experiment. If a pound of water at 80° is mixed with a pound of water at zero, the temperature of the mixture is 40°. But if a pound of pounded *ice* at zero is mixed with a pound of water at 80°, the ice melts, and two pounds of water at zero are obtained. Consequently, the mere change of a pound of ice to a pound of water at the same temperature requires as much heat as will raise a pound of water through 80°. This quantity of heat represents the latent heat of the fusion of ice, or the latent heat of water.

Every liquid has its own latent heat, and in the chapter on Calorimetry we shall show how this is determined.

309. **Solution.**—A body is said to *dissolve* when it becomes liquid in consequence of an affinity between its molecules and those of a liquid. Gum arabic, sugar, and most salts dissolve in water.

During solution, as well as during fusion, a certain quantity of heat always becomes latent, and hence it is that the solution of a substance usually produces a diminution of temperature. In certain cases, however, instead of the temperature being lowered, it actually rises, as when caustic potass is dissolved in water. This depends upon the fact that two simultaneous and contrary phenomena are produced. The first is the passage from the solid to the liquid condition, which always lowers the temperature. The second is the *chemical* combination of the body dissolved with the liquid, and which, as in the case of all chemical combinations, produces an increase of temperature. Consequently, as the one or the other of these effects predominates, or as they are equal, the temperature either rises, or sinks, or remains constant.

310. **Solidification.**—*Solidification* or *congelation* is the passage of a body from the liquid to the solid state. This phenomenon is regulated by the two following laws :—

I. *Every body, under the same pressure, solidifies at a fixed temperature, which is the same as that of fusion.*

II. *From the commencement to the end of the solidification, the temperature of a liquid remains constant.*

Certain bodies, more especially some of the fats, present an exception to the first law, in so far that by repeated fusions they seem to undergo a molecular change which alters their melting point.

The second law is a consequence of the fact that the latent heat absorbed during fusion becomes free at the moment of solidification.

Many liquids, such as alcohol, ether, and bisulphide of carbon, do not solidify even at the lowest known temperature. But M. Despretz, by the

cold produced by a mixture of liquid protoxide of nitrogen, solid carbonic acid, and ether, has reduced alcohol to such a consistence that the vessel containing it could be inverted without losing the liquid.

311. **Crystallisation.**—Generally speaking, bodies which pass slowly from the liquid to the solid state assume regular geometrical forms, such as the cube, prisms, rhombohedrons, etc.; these are called *crystals*. If the crystals are formed from a body in fusion, such as sulphur or bismuth, the crystallisation is said to take place by the *dry way*. But if the crytallisation takes place from the slow evaporation of a solution of a salt, it is said to be by the *moist way*. Snow, ice, and many salts present examples of crystallisation.

312. **Retardation of the point of solidification.**—The freezing point of pure water can be diminished by several degrees, if the water be previously freed from air by boiling and then kept in a perfectly still place. In fact it may be cooled to -15° C., and even below, without freezing. But when it is slightly agitated, the liquid soon solidifies. The smaller the quantity of liquid the lower the temperature to which it can be cooled, and the greater the mechanical disturbance it supports without freezing. Fournet has observed the frequent occurrence of mists formed of particles of liquid matter suspended in an atmosphere whose temperature is 10° or even 15° below zero.

A very rapid agitation also prevents the formation of ice. The same is the case with all actions which, hindering the molecules in their movements, do not permit them to arrange themselves in the conditions necessary for the solid state. M. Despretz was able to lower the temperature of water contained in fine capillary tubes to -20° without their solidifying. This experiment shows how it is that plants in many cases do not become frozen, as the sap is contained in very fine capillary vessels. Finally M. Mousson has found that a powerful pressure not only retards the freezing of water, but prevents its complete solidification. In this case the pressure opposes the tendency of the water to expand on freezing, and thus virtually lowers the point of solidification.

If water contains salts or other foreign bodies its freezing point is lowered. Sea water freezes at $-2{\cdot}5^\circ$ to -3° C.; the ice which forms is quite pure, and a saturated solution remains. In Finland advantage is taken of this property to concentrate sea water for the purpose of extracting salt from it. If water contains alcohol, precisely analogous phenomena are observed: the ice formed is pure, and all the alcohol is contained in the residue.

Dufour has observed some very curious cases of liquids cooled out of contact with solid bodies. His mode of experimenting was to place the liquid in another of the same specific gravity but of lower melting point, and in which it was insoluble. Spheres of water, for instance, suspended in a mixture of chloroform and oil, usually solidified between -4° and -12°, while some smaller globules cooled down to -18° or -20°. Contact with a fragment of ice immediately set up congelation. Globules of sulphur (which solidifies at 115°) remained liquid at 40°; and globules of phosphorus (solidifying point 42°) at 20°.

When a liquid solidifies after being cooled below its normal freezing point, the solidification takes place very rapidly, and is accompanied by a disengagement of heat, often sufficient to raise its temperature from the point at which solidification begins up to its ordinary freezing point. This is well seen in the case of hyposulphite of sodium, which melts in its own water of crystallisation at 45°, and when carefully cooled will remain liquid at the ordinary temperature of the atmosphere. If it then be made to solidify by agitation, or by adding a small fragment of the solid salt, the rise of temperature is distinctly felt by the hand. In this case the heat which had become latent in the process of liquefaction again becomes free.

313. **Change of volume on solidification and liquefaction**. –The rate of expansion of bodies generally increases as they approach their melting points, and is in most cases followed by a further expansion at the moment of liquefaction, so that the liquid occupies a greater volume than the solid from which it is formed. Phosphorus, for instance, increases about 3·4 per cent. on liquefaction : that is, 100 volumes of solid phosphorus at 44° (the melting point) become 103·4 at the same temperature when melted. Sulphur expands about 5 per cent. on liquefying, and stearic acid about 11 per cent.

Water presents a remarkable exception ; it expands on the moment of solidifying, or contracts on melting, by about 10 per cent. One volume of ice at 0° gives 0·908 of water at 0°, or 1 volume of water at 0° gives 1·102 of ice at the same temperature. In consequence of this expansion, ice floats on the surface of water.

The increase of volume in the formation of ice is accompanied by an expansive force which sometimes produces powerful mechanical effects, of which the bursting of water-pipes and the breaking of jugs containing water are familiar examples. The splitting of stones, rocks, and the swelling up of moist ground during frost, are caused by the fact that water penetrates into the pores and there becomes frozen.

The expansive force of ice was strikingly shown by some experiments of Major Williams, in Canada. Having quite filled a 13-inch iron bomb-shell with water, he firmly closed the touch-hole with an iron plug weighing 3 pounds, and exposed it in this state to the frost. After some time the iron plug was forced out with a loud explosion, and thrown to a distance of 415 feet, and a cylinder of ice 8 inches long issued from the opening. In another case the shell burst before the plug was driven out, and in this case a sheet of ice spread out all round the crack. It is possible that under the great pressure some of the water still remained liquid up to the time at which the resistance was overcome ; that it then issued from the shell in a liquid state, but at a temperature below 0°, and therefore instantly began to solidify when the pressure was removed, and thus retained the shape of the orifice whence it issued.

Cast-iron, bismuth, and antimony expand on solidifying like water, and can thus be used for casting ; but gold, silver, and copper contract, and hence coins of these metals cannot be cast, but must be stamped with a die.

314. **Freezing mixtures.**—The absorption of heat in the passage of bodies from the solid to the liquid state has been used to produce artificial cold. This is effected by mixing together bodies which have an affinity for each other, and of which one at least is solid, such as water and a salt, ice and a salt, or an acid and a salt. Chemical affinity accelerates the fusion ; the portion which melts robs the rest of the mixture of a large quantity of sensible heat, which thus becomes latent. In many cases a very considerable diminution of temperature is produced.

The following table gives the names of the substances mixed, their proportions, and the corresponding diminutions of temperature :—

Substances.	Parts by weight.	Reduction of temperature.
Sulphate of sodium Hydrochloric acid	8 5	$+10°$ to $-17°$
Pounded ice or snow Common salt	2 1	$+10°$ to $-18°$
Sulphate of sodium Dilute nitric acid	3 2	$+10°$ to $-19°$
Sulphate of sodium Nitrate of ammonium Dilute nitric acid	6 5 4	$+10°$ to $-26°$
Phosphate of sodium Dilute nitric acid	9 4	$+10°$ to $-29°$

If the substances taken be themselves first previously cooled down, a still more considerable diminution of temperature is occasioned.

Freezing mixtures are frequently used in chemistry, in physics, and in domestic economy. The portable ice-making machines which have come in use during the last few years, consist of a cylindrical metallic vessel divided into four concentric compartments. In the central one is placed the water to be frozen ; in the next there is the freezing mixture, which usually consists of sulphate of sodium and hydrochloric acid ; 6 pounds of the former and 5 of the latter will make 5 to 6 pounds of ice in an hour. The third compartment also contains water, and the outside one contains some badly-conducting substance, such as cotton, to prevent the influence of the external temperature. The best effect is obtained when pretty large quantities (2 or 3 pounds) of the mixture are used, and when they are intimately mixed. It is also advantageous to use the machines for a series of successive operations.

VAPOURS. MEASUREMENT OF THEIR TENSION.

315. **Vapours.**—We have already seen (138) that *vapours* are the aëriform fluids into which volatile substances, such as ether, alcohol, water, and mercury, are changed by the absorption of heat. *Volatile liquids* are those which thus possess the property of passing into the

aëriform state, and *fixed liquids*, those which do not form vapours at any temperature without undergoing chemical decomposition, such as the fatty oils. There are some solids, such as ice, arsenic, camphor, and in general all odoriferous solid substances, which can directly form vapours without first becoming liquid.

Vapours are transparent like gases, and generally colourless: there are only a few coloured liquids, which also give coloured vapours.

316. **Vaporisation.**—The passage of a liquid into the gaseous state is designated by the general term *vaporisation*; the term *evaporation* especially refers to the slow production of vapour at the free surface of a liquid, and *boiling* to its rapid production in the mass of the liquid itself. We shall presently see (329) that at the ordinary atmospheric pressure, ebullition, like fusion, takes place at a definite temperature. This is not the case with evaporation, which takes place even with the same liquid at very different temperatures, although the formation of a vapour seems to cease below a certain point. Mercury, for example, gives no vapour below $-10°$, nor sulphuric acid below $30°$.

317. **Elastic force of vapours.**—Like gases, vapours have a certain elastic force, in virtue of which they exert pressures on the sides of vessels in which they are contained. The tension of vapours may be demonstrated by the following experiment:—A quantity of mercury is placed in a bent glass tube (fig. 249) the shorter leg of which is closed; a few drops of ether are then passed into the closed leg, and the tube immersed in a water bath at a temperature of about $45°$. The mercury then sinks slowly in the short branch, and the space *ab* is filled with a gas which has all the appearance of air, and whose elastic force counterbalances the pressure of the column of mercury *cd*, and the atmospheric pressure on *d*. This gas is the vapour of ether. If the water be cooled, or if the tube be removed from the bath, the vapour which fills the space *ab* disappears, and the drop of ether is reproduced. If, on the contrary, the bath be heated still higher, the level of the mercury descends below *b*, indicating an increased tension.

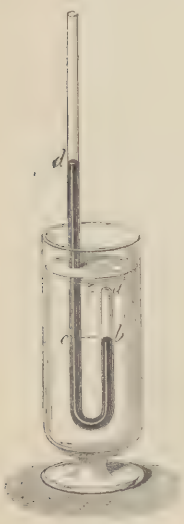


Fig. 249.

318. **Formation of vapours in a vacuum.**—In the previous experiment the liquid changed very slowly into the vaporous condition; the same is the case when a liquid is freely exposed to the air. In both cases the atmosphere is an obstacle to the vaporisation. In a vacuum there is no resistance, and the formation of vapours is instantaneous, as is seen in the following experiment:—Four barometer tubes, filled with mercury, are immersed in the same trough (fig. 250). One of them, A, serves as a barometer, and a few drops of water, alcohol, and ether are respectively introduced

into the tubes, B, C, D. When the liquids reach the vacuum a depression of the mercury is at once produced. And as this depression cannot be produced by the weight of the liquid, which is an infinitely small fraction of the weight of the displaced mercury, it must be due to the formation of some vapour whose elastic force has depressed the mercurial column.

Fig. 250.

The experiment also shows that the depression is not the same in all the tubes; it is greater in the case of alcohol than of water, and greater with ether than with alcohol. We consequently obtain the two following laws for the formation of vapours:—

I. *In a vacuum all volatile liquids are instantaneously converted into vapour.*

II. *At the same temperature the vapours of different liquids have different elastic forces.*

For example, at 20°, the tension of ether vapour is 25 times as great as that of aqueous vapour.

319. **Saturated vapours. Maximum of tension.**—When a very small quantity of a volatile liquid, such as ether, is introduced into a barometer tube, it is at once completely vaporised, and the mercurial column is not depressed to its full extent; for if some more ether be introduced the depression increases. By continuing the addition of ether, it finally ceases to vaporise, and remains in the liquid state. There is therefore, for a certain temperature, a limit to the quantity of vapour which can be formed in a given space. This space is accordingly said to be *saturated.* Further, when the vaporisation of the ether ceases, the depression of the mercurial column stops. And hence there is a limit to the tension of the vapour, a limit which, as we shall presently see (322), varies with the temperature, but which for a given temperature is *independent of the pressure.*

To show that, in a closed space, saturated with vapour and containing liquid *in excess*, the temperature remaining constant, there is a *maximum of tension* which the vapour cannot exceed, a barometric tube is used which dips in a deep bath (fig. 251). This tube is filled with mercury, and then so much ether is added as to be in excess after the Torricellian vacuum is saturated. The height of the mercurial column is next noted by means of the scale graduated on the tube itself. Now, whether the tube be depressed, which tends to compress the vapour, or whether it be

raised which tends to expand it, the height of the mercurial column is constant. The tension of the vapour remains constant in the two cases, for the depression neither increases nor diminishes it. Hence it is concluded that when the saturated vapour is compressed, a portion returns to the liquid state; that when, on the other hand, the pressure is diminished, a portion of the excess of liquid vaporises, and the space occupied by the vapour is again saturated; but in both cases the tension and the density of the vapour remain constant.

320. **Non-saturated vapours.**—From what has been said, vapours present two very different states, according as they are saturated or not. In the first case, where they are saturated and in contact with the liquid, they differ completely from gases, since for a given temperature they can neither be compressed nor expanded; their elastic force and their density remain constant.

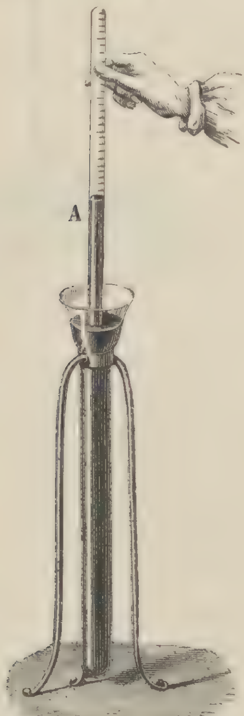


Fig. 251.

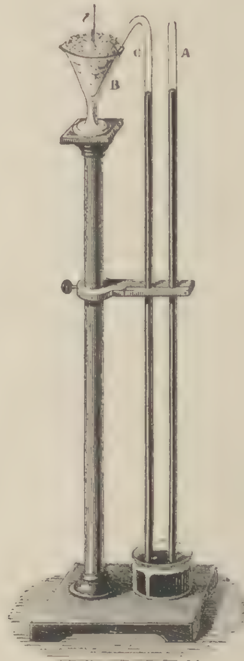


Fig. 252.

In the second case, on the contrary, where they are not saturated, they exactly resemble gases. For if the experiments (fig. 251) be repeated, only a small quantity of ether being introduced, so that the vapour is

not saturated, and if the tube be then slightly raised, the level of the mercury is seen to rise, which shows that the elastic force of the vapour has diminished. Similarly, by immersing the tube still more, the level of the mercury sinks. The vapour consequently behaves just as a gas would do, its tension diminishes when the volume increases, and *vice versa*; and as in both cases the volume of the vapour is inversely as the pressure, it is concluded that *non-saturated vapours obey Boyle's law.*

When a non-saturated vapour is heated, its volume increases like that of a gas: and the number 0·00366, which is the coefficient of the expansion of air, may be taken for that of vapours.

Hence we see that the physical properties of unsaturated vapours are comparable with those of permanent gases, and that the formulæ for the compressibility and expansibility of gases (163 and 299) also apply to unsaturated vapours. But it must not be forgotten that there is always a limit of pressure or of cooling at which unsaturated vapours pass into a state of saturation, and that they have then a maximum of tension and density which can only be exceeded when the temperature rises while they are in contact with the liquid.

321. **Tension of aqueous vapours below zero.**—For the sake of measuring the elastic force of aqueous vapour below zero, Gay-Lussac used two barometer tubes filled with mercury, and placed in the same bath (fig. 252). The straight tube A serves as a barometer; the other, B, is bent, so that part of the Torricellian vacuum can be surrounded by a freezing mixture (314). When a little water is admitted into the bent tube, the level of the mercury sinks below that in the tube A to an extent which varies with the temperature of the freezing mixture.

At $0°$ the depression is	. . .	4·60 millimeters.
„ $-10°$ „ „	. . . .	1·96 „
„ $-20°$ „ „	. . . .	0·84 „
„ $-30°$ „ „	. . . .	0·36 „

These depressions, which must be due to the tension of aqueous vapour in the space BC, show that even at low temperatures there is aqueous vapour in the atmosphere.

Although in the above experiment the part B and the part C are not both immersed in the freezing mixture, we shall presently see that when two communicating vessels are at different temperatures, the tension of the vapour is the same in both, and always corresponds to the lowest temperature.

That water evaporates even below zero follows from the fact, that wet linen exposed to the air during frost first becomes stiff and then dry, showing that the particles of water evaporate even after the latter has been converted into ice.

322. **Tension of aqueous vapour between zero and one hundred degrees.**—i. *Dalton's method.* Dalton measured the elastic force of aqueous vapour between $0°$ and $100°$ by means of the apparatus represented in fig. 253. Two barometer tubes, A and B, are filled with mercury, and inverted in an iron bath full of mercury, and placed on a furnace.

The tube A contains a small quantity of water. The tubes are supported in a cylindrical vessel full of water, the temperature of which is indicated by the thermometer. The bath being gradually heated, the water in the cylinder becomes heated too; the water which is in the tube A vaporises, and in proportion as the tension of its vapour increases, the mercury sinks. The depressions of the mercury corresponding to each degree of the thermometer are indicated on the scale E, and in this manner a table of the elastic forces between zero and 100° has been constructed.

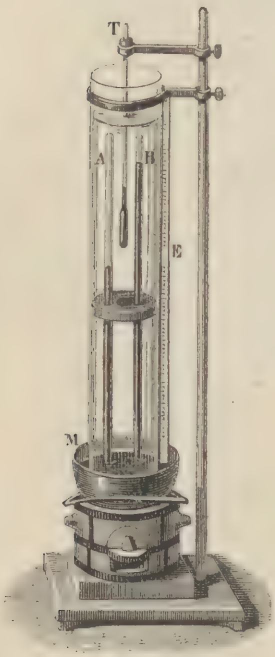


Fig. 253.

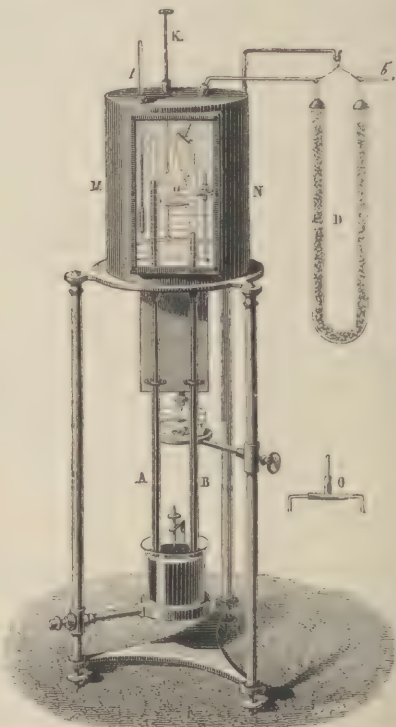


Fig. 254.

ii. *Regnault's method.*—Dalton's method is wanting in precision, for the liquid in the cylinder has not everywhere the same temperature, and consequently the exact temperature of the aqueous vapour is not indicated. Regnault's apparatus is a modification of that of Dalton. The cylindrical vessel is replaced by a large cylindrical zinc drum, MN (fig. 254), in the bottom of which are two tubulars. The tubes A and B pass through these tubulures, and are fixed by caoutchouc collars. The tube containing

vapour, B, is connected with a flask, *a*, by means of a brass three-way tube, O. The third limb of this tube is connected with a drying tube, D, containing pumice impregnated with sulphuric acid, which is connected with the air pump.

When the flask *a* contains some water, a small portion is distilled into B by gently heating the flask. Exhausting them by means of the air pump, the water distils continuously from the flask and from the barometric tube towards D, which condenses the vapours. After having vaporised some quantity of water, and it is thought that the air in the tube is withdrawn, the capillary tube which connects B with the three-way tube is sealed. The tube B being thus closed, it is experimented with, as in Dalton's method.

The drum MN, being filled with water, is gently heated by a spirit lamp, which is separated from the tubes by a wooden screen. By means of a stirrer, K, all parts of the liquid are kept at the same temperature. In the side of the drum is a glass window, through which the height of the mercury in the tubes can be read off by means of a cathetometer; from the difference in these heights, reduced to zero, the tension of vapour is deduced. By means of this apparatus, the elastic force of vapour between 0° and 50° has been determined with accuracy.

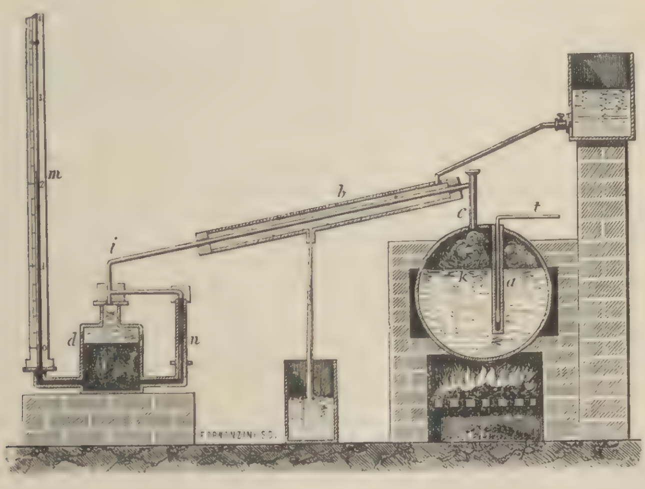


Fig. 255.

323. **Tension of aqueous vapour above one hundred degrees.**—Two methods have been employed for determining the tension of aqueous vapour at temperatures above 100°, the one by Dulong and Arago, in 1830, and the other by Regnault, in 1844.

Fig. 255 represents a vertical section of the apparatus used by Dulong

and Arago. It consisted of a copper boiler, *k*, with very thick sides, and of about 20 gallons capacity. Two gun-barrels, *a*, of which only one is seen in the drawing, were firmly fixed in the sides of the boiler, and plunged in the water. The gun-barrels were closed below, and contained mercury, in which were placed thermometers, *t*, indicating the temperature of the water and of the vapour. The tension of the vapour was measured by means of a manometer with compressed air, *m*, previously graduated (167) and fitted into an iron vessel, *d*, filled with mercury. In order to see the height of the mercury in the vessel, it was connected above and below with a glass tube, *n*, in which the level was always the same as in the bath. A copper tube, *i*, connected the upper part of the vessel, *d*, with a vertical tube, *c*, fitted in the boiler. The tube *i* and the upper part of the bath *d* were filled with water, which was kept cool by means of a current of cold water flowing from a reservoir and circulating through the tube *b*.

The vapour which was disengaged from the tube *c* exercised a pressure on the water of the tube *i*; this pressure was transmitted to the water and to the mercury in the bath *d*, and the mercury rose in the manometer. By noting on the manometer the pressures corresponding to each degree of the thermometer, Dulong and Arago were able to make a direct measurement of the tension up to 24 atmospheres, and the tension from thence to 50 atmospheres was determined by calculation.

324. **Tension of vapour below and above one hundred degrees.**—Regnault has devised a method by which the tension of vapour may be measured at temperatures either below or above 100°. It depends on the principle that when a liquid boils, the tension of the vapour is equal to the pressure it supports (332). If, therefore, the temperature and the corresponding pressure are known, the question is solved, and the method merely consists in causing water to boil in a vessel under a given pressure, and measuring the corresponding temperature.

The apparatus consists of a copper retort, C (fig. 256), hermetically sealed, and about two-thirds full of water. In the cover there are four thermometers, two of which just dip into the water, and two descend almost to the bottom. By means of a tube, AB, the retort C is connected with a glass globe, M, of about 6 gallons capacity, and full of air. The tube AB passes through a metallic cylinder, D, through which a current of cold water is constantly flowing from the reservoir E. To the upper part of the globe a tube with two branches is attached, one of which is connected with a manometer, O; the other tube, HH′, which is of lead, can be attached either to an exhausting or a condensing air pump, according as the air in the globe is to be rarefied or condensed. The reservoir K, in which is the globe, contains water of the temperature of the surrounding air.

If the elastic force of aqueous vapour below 100° is to be measured, the end H′ of the leaden pipe is connected with the plate of the air pump, and the air in the globe M, and consequently that in the retort C, is

rarefied. The retort being gently heated, the water begins to boil at a temperature below 100°, in consequence of the diminished pressure. And

Fig. 256.

since the vapour is condensed in the tube AB, which is always cool, the pressure originally indicated by the manometer does not increase, and therefore the tension of the vapour during ebullition remains equal to the pressure on the liquid.

A little air is then allowed to enter; this alters the pressure, and the liquid boils at a new temperature; both these are read off, and the experiment repeated as often as desired up to 100°.

In order to measure the tension above 100°, the tube H′ is connected with a condensing pump, by means of which the air in the globe M and that in the vessel C are exposed to successive pressures, higher than the atmospheres. The ebullition is retarded (332), and it is only necessary to observe the difference in the height of the mercury in the two tubes of the manometer O, and the corresponding temperature, in order to obtain the tension for a given temperature.

The following tables by M. Regnault give the tension of aqueous vapour from − 10° to 101°.

Tensions of aqueous vapour from $-10°$ *to* 101° *C.*

Temperatures	Tensions in millimeters	Temperatures	Tensions in millimeters	Temperatures	Tensions in millimeters	Temperatures	Tensions in millimeters
$-10°$	2·078	12°	10·457	29°	29·782	85°	433·41
8	2·456	13	11·062	30	31·548	90	525·45
6	2·890	14	11·906	31	33·405	91	545·78
4	3·387	15	12·699	32	35·359	92	566·76
2	3·955	16	13·635	33	37·410	93	588·41
0	4·600	17	14·421	34	39·565	94	610·74
+1	4·940	18	15·357	35	41·827	95	633·78
2	5·302	19	16·346	40	54·906	96	657·54
3	5·687	20	17·391	45	71·391	97	682·03
4	6·097	21	18·495	50	91·982	98	707·26
5	6·534	22	19·659	55	117·478	98·5	720·15
6	6·998	23	20·888	60	148·791	99·0	733·21
7	7·492	24	22·184	65	186·945	99·5	746·50
8	8·017	25	23·550	70	233·093	100·0	760·00
9	8·574	26	24·998	75	288·517	100·5	773·71
10	9·165	27	26·505	80	354·643	101·0	787·63
11	9·792	28	28·101				

In the second table the numbers were obtained by direct observation up to 24 atmospheres; the others were calculated by the aid of a formula of interpolation.

Tensions in atmospheres from 100° *to* 230·9°.

Temperature	Number of atmospheres	Temperature	Number of atmospheres	Temperature	Number of atmospheres	Temperature	Number of atmospheres
100·0°	1	170·8°	8	198·8°	15	217·9°	22
112·2	1½	175·8	9	201·9	16	220·3	23
120.6	2	180·3	10	204·9	17	222·5	24
133·9	3	184·5	11	207·7	18	224·7	25
144·0	4	188·4	12	210·4	19	226·8	26
152·2	5	192·1	13	213·0	20	228·9	27
159·2	6	195·5	14	215·5	21	230·9	28
165·3	7						

These tables show that the elastic force increases much more rapidly than the temperature. The law which regulates this increase is not accurately known.

325. **Tension of the vapours of different liquids.**—Regnault has

determined the elastic force at various temperatures of a certain number of liquids which are given in the following table :—

Liquids	Temperature	Tensions in millimeters	Liquids	Temperature	Tensions in millimeters
Mercury .	50°	0·11	Ether . .	−20°	9
	100	0·74		0	182
Alcohol .	0	13		60	1728
	50	220	Sulphurous acid	100	4920
	100	1685		−20	479
Bisulphide of carbon	−20	43		0	1165
	0	132	Ammonia .	60	8124
	60	1164		−30	441
	100	3329		−30	4373
				0	7709

326. **Tension of the vapours of mixed liquids.**—Regnault's experiments on the tension of the vapour of mixed liquids prove that (i.) when two liquids exert no solvent action on each other—such as water and *bisulphide of carbon*, or water and *benzole*—the tension of the vapour which rises from them is nearly equal to the sum of the tensions of the two separate liquids at the same temperature ; (ii.) with water and *ether*, which partially dissolve each other, the tension of the mixture is much less than the sum of the tensions of the separate liquids, being scarcely equal to that of the ether alone ; (iii.) when two liquids dissolve in all proportions, as ether and bisulphide of carbon, or water and alcohol, the tension of the vapour of the mixed liquid is intermediate between the tensions of the separate liquids.

Wüllner has shown that the tension of aqueous vapour emitted from a saline solution, as compared with that of pure water, is diminished by an amount proportional to the quantity of anhydrous salt dissolved, when the salt crystallises without water or yields efflorescent crystals ; when the salt is deliquescent, or has a powerful attraction for water, the reduction of tension is proportional to the quantity of crystallised salt.

327. **Tension in two communicating vessels at different temperatures.**—When two vessels containing the same liquid, but at different temperatures, are connected with each other, the elastic force is not that corresponding to the mean of the two temperatures, as would naturally be supposed. Thus, if there are two globes, fig. 257, one, A, containing water kept at zero by means of melting ice, the other, B, containing water at 100°, the tension, as long as the globes are not connected, is 4 to 6 millimeters in the first, and 760 millimeters in the second. But when they are connected by opening the stopcock C, the vapour in the globe B, from its greater tension, passes into the other globe, and is there condensed, so that the vapour in B can never reach a higher temperature than that in the globe A. The liquid simply distils from B towards A without any increase of tension.

From this experiment the general principle may be deduced that *when two vessels containing the same liquid, but at different temperatures, are connected, the tension is identical in both vessels, and is the same as that corresponding to the lower temperature.* An application of this principle has been made by Watt in the condenser of the steam-engine.

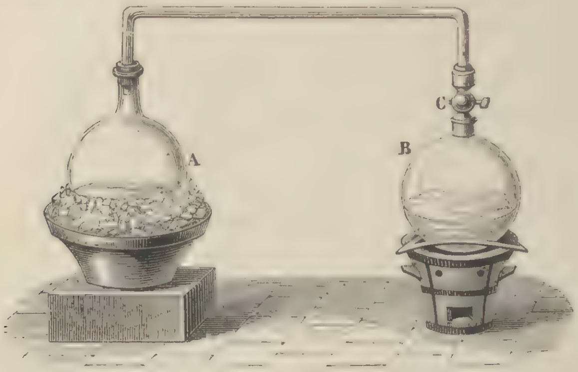


Fig. 257.

328. **Evaporation. Causes which accelerate it.**—*Evaporation*, as has been already stated (316), is the slow production of vapour at the surface of a liquid. It is in consequence of this evaporation that wet clothes dry when exposed to the air, and that open vessels containing water become emptied. The vapours which, rising in the atmosphere, condense, and becoming clouds fall as rain, are due to the evaporation from the seas, lakes, rivers, and the soil.

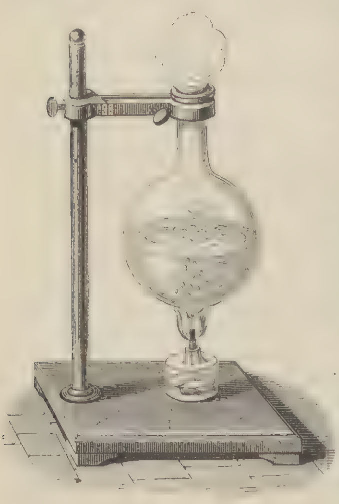


Fig. 258.

Four causes influence the rapidity of the evaporation of a liquid : i. the temperature; ii. the quantity of the same vapour in the surrounding atmosphere; iii. the renewal of this atmosphere; iv. the extent of the surface of evaporation.

Increase of temperature accelerates the evaporation by increasing the elastic force of the vapours.

In order to understand the influence of the second cause, it is to be observed that no evaporation could take place in a space already saturated with vapour of the same liquid, and that it would reach its maximum in air completely freed from this vapour. It therefore follows that between these two extremes the rapidity of evapo-

ration varies according as the surrounding atmosphere is already more or less charged with the same vapour.

The effect of the renewal of this atmosphere is similarly explained ; for if the air or gas, which surrounds the liquid, is not renewed, it soon becomes saturated, and evaporation ceases.

The influence of the fourth cause is self-evident.

329. **Laws of ebullition.**—*Ebullition*, or *boiling*, is the rapid production of elastic bubbles of vapour in the mass of a liquid itself.

When a liquid, water for example, is heated at the lower part of a vessel, the first bubbles are due to the disengagement of air which had previously been absorbed. Small bubbles of vapour then begin to rise from the heated parts of the sides, but as they pass through the upper layers, the temperature of which is lower, they condense before reaching the surface. The formation and successive condensation of these first bubbles occasion the *singing* noticed in liquids before they begin to boil. Lastly, large bubbles rise and burst on the surface, and this constitutes the phenomenon of ebullition (fig. 258).

The laws of ebullition have been determined experimentally, and are as follows :

I. *The temperature of ebullition, or the boiling point, increases with the pressure.*

II. *For a given pressure ebullition commences at a certain temperature, which varies in different liquids, but which, for equal pressures, is always the same in the same liquid.*

III. *Whatever be the intensity of the source of heat, as soon as ebullition commences, the temperature of the liquid remains stationary.*

Boiling points under the pressure 760 *millimeters.*

Sulphurous acid	−10°	Turpentine	160°
Chloride of ethyle	+11	Butyric acid	157
Ether	37	Phosphorus	290
Bisulphide of carbon	48	Strong sulphuric acid	325
Bromine	63	Mercury	320
Alcohol	78	Sulphur	447
Distilled water	100	Cadmium	860
Acetic acid	117	Zinc	1040

There are many causes which influence the boiling point of a liquid, such as the substances dissolved, the nature of the vessel, and the pressure. We shall illustrate the effects of these different causes, more particularly on water.

Kopp has pointed out that in analogous chemical compounds the same difference in chemical composition frequently involves the same difference of boiling points ; and he has endeavoured to show that in a very extensive series of compounds the difference of CH^2 is attended by a difference of 19° C. in the boiling point.

330. **Influence of substances in solution on the boiling point.**—The ebullition of a liquid is the more retarded the greater the quantity

of any substance it may contain in solution, provided that the substance be not volatile, or, at all events, be less volatile than the liquid itself. Water which boils at 100° when pure, boils at the following temperatures when saturated with different salts :—

Water saturated with common salt . .	boils at	109°
,, ,, nitrate of potassium	,,	116
,, ,, carbonate of potassium	,,	135
,, ,, chloride of calcium	,,	179

Acids in solution present analogous results ; but substances merely mechanically suspended, such as earthy matters, bran, wooden shavings, etc., do not affect the boiling point.

Dissolved air exerts a very marked influence on the boiling point of water. Deluc first observed that water freed from air by ebullition, and placed in a flask with a long neck, could be raised to 112° without boiling. M. Donny found that water deprived of air and sealed up in a long glass tube may be heated at one end as high as 138° without boiling, and is then suddenly and violently thrown to the other by a burst of vapour.

When a liquid is suspended in another of the same specific gravity, but higher boiling point, it may be raised far beyond its boiling point without the formation of a trace of vapour. Dufour has made a number of valuable experiments on this subject ; he used in the case of water a mixture of oil of cloves and linseed oil, and placed in it globules of water, and then gradually heated the oil ; in this way ebullition rarely set in below 110° or 115°, very commonly globules of 10 millimeters diameter reached a temperature of 120° or 130°, while very small globules of 1 to 3 millimeters reached the temperature of 175°, a temperature at which the tension of vapour on a free surface is 8 or 9 atmospheres.

At these high temperatures the contact of a solid body, or the production of gas bubbles in the liquid, occasioned a sudden vaporisation of the globule, accompanied by a sound like the hissing of a hot iron in water.

Saturated aqueous solutions of sulphate of copper, chloride of sodium, etc., remained liquid at a temperature far beyond their boiling point, when immersed in melted stearic acid. In like manner, globules of chloroform (which boils at 61°) suspended in a solution of chloride of zinc could be heated to 97° or 98° without boiling.

It is a disputed question as to what is the temperature of the vapour from boiling saturated saline solutions. It has been stated by Rudberg to be that of pure water boiling under the same pressure ; the most recent experiments of Magnus seem to show, however, that this is not the case, but that the vapour of boiling solutions is hotter than that of pure water ; and that the temperature rises as the solutions become more concentrated, and therefore boil at higher temperatures. Nevertheless, the vapour was always found somewhat cooler than the mass of the boiling solution, and the difference was greater at high than at low temperatures.

331. **Influence of the nature of the vessel on the boiling point.**—Gay-Lussac observed that water in a glass vessel required a higher temperature for ebullition than in a metal one. Taking the temperature of boiling water in a copper vessel at 100°, its boiling point in a glass vessel was found to be 101°; and if the glass vessel had been previously cleaned by means of sulphuric acid and of potass, the temperature would rise to 105°, or even to 106°, before ebullition commenced. A piece of metal placed in the bottom of the vessel was always sufficient to lower the temperature to 100°, and at the same time to prevent the violent concussions which accompany the ebullition of saline or acid solutions in glass vessels. Whatever be the boiling point of water, the temperature of its vapour is uninfluenced by the substance of the vessels.

332. **Influence of pressure on the boiling point.**—We see from the table of tensions (324) that at 100°, the temperature at which water boils under a pressure of 760 millimeters, aqueous vapour has a tension exactly equal to this pressure. This principle is general, and may be thus enunciated: *A liquid boils when the tension of its vapour is equal to the pressure it supports.* Consequently as the pressure increases or diminishes, the tension of the vapour, and therefore the temperature necessary for ebullition, must increase or diminish.

Fig. 259.

In order to show that the boiling point is lower under diminished pressure, a small dish containing water at 30° is placed under the receiver of an air-pump, which is then exhausted. The liquid soon begins to boil, the vapour formed being pumped out as rapidly as it is generated.

A paradoxical but very simple experiment also well illustrates the dependence of the boiling point on the pressure. In a glass flask, water is boiled for some time, and when all air has been expelled by the steam, the flask is closed by a cork and inverted as shown in fig. 259. If the bottom is then cooled by a stream of cold water from a sponge, the water begins to boil again. This arises from the condensation of the steam above the surface of the water, by which a partial vacuum is produced.

It is in consequence of this diminution of pressure that liquids boil on high mountains at lower temperatures. On Mont Blanc, for example, water boils at 84°, and at Quito at 90°.

On the more rapid evaporation of water under feeble pressures is

based the use of the air pump in concentrating those solutions which either cannot bear a high degree of heat, or which can be more cheaply evaporated in an exhausted space. Mr. Howard made a most important and useful application of this principle in the manufacture of sugar. The syrup, in his method, is enclosed in an air-tight vessel, which is exhausted by a steam-engine. The evaporation consequently goes on at a lower temperature, which secures the syrup from injury. The same plan is adopted in evaporating the juice of certain plants used in preparing medicinal extracts.

On the other hand, ebullition is retarded by increasing the pressure; under a pressure of two atmospheres, for example, water only boils at 120·6°.

333. **Franklin's experiment.**—The influence of pressure on ebullition may further be illustrated by means of an experiment of Franklin's. The apparatus consists of a bulb, *a*, and a tube, *b*, joined by a tube of smaller dimensions (fig. 260). The tube *b* is drawn out, and the apparatus filled with water, which is then in great part boiled away by means of a spirit lamp. When it has been boiled sufficiently long to expel all the air, the tube *b* is sealed. There is then a vacuum in the apparatus, or rather there is a pressure due to the tension of aqueous vapour, which at ordinary temperatures is very small. Consequently, if the bulb *a* be placed in the hand, the heat is sufficient to produce a tension which drives the water into the tube *b*, and causes a brisk ebullition.

Fig. 260.

334. **Measurement of heights by the boiling point.**—From the connection between the boiling point of water and the pressure, the heights of mountains may be measured by the thermometer instead of by the barometer. Suppose, for example, it is found that water boils on the summit of a mountain at 90°, and at its base at 98°; at these temperatures the elastic force or tension of the vapour is equal to that of the pressure on the liquid, that is, to the pressure of the atmosphere at the two places respectively. Now the tensions of aqueous vapour for various temperatures have been determined, and accordingly the tensions corresponding to the above temperatures are sought in the tables. These numbers represent the atmospheric pressures at the two places: in other words, they give the barometric heights, and from these the height of the mountain may be calculated by the method already given (162). An ascent of about 1080 feet produces a diminution of 1° C. in the boiling point.

The instruments used for this purpose are called *thermo-barometers*, or *hypsometers*, and were first applied by Wollaston. They consist essentially of a small metallic vessel for boiling water, fitted with very delicate thermometers, which are only graduated from 80° to 100°;

so that, each degree occupying a considerable space on the scale, the 10ths, and even the 100ths, of a degree may be estimated, and thus it is possible to determine the height of a place by means of the boiling point to within about 10 feet.

335. **Formation of vapour in a closed tube.**—We have hitherto considered vapours as being produced in an indefinite space, or where they could expand freely, and it is only under this condition that ebullition can take place. In a closed vessel the vapours produced finding no issue, their tension and their density increase with the temperature, but the rapid disengagement of vapour which constitutes ebullition is impossible. Hence, while the temperature of a liquid in an open vessel can never exceed that of ebullition, in a closed vessel it may be much higher. The liquid state has, nevertheless, a limit; for, according to experiments by Cagniard-Latour, if either water, alcohol, or ether be placed in strong glass tubes, which are hermetically sealed after the air has been expelled by boiling, when these tubes are exposed to a sufficient degree of heat, a moment is reached at which the liquid suddenly disappears, and is converted into vapour at 200°, occupying a space less than double its volume in the liquid state, and that the tension was then 38 atmospheres.

Alcohol which half fills a tube is converted into vapour at 207° C. If a glass tube about half filled with water, in which some carbonate of soda has been dissolved, to diminish the action of the water in the glass, be heated, it is completely vaporised at about the temperature of melting zinc.

When chloride of ethyle was heated in a very thick sealed tube, the upper surface ceased to be distinct at 170°, and was replaced by an ill-defined nebulous zone. As the temperature rose this zone increased in width in both directions, becoming at the same time more transparent; after a time the liquid was completely vaporised, and the tube became transparent and seemingly empty. On cooling, the phenomena were reproduced in the opposite order. Similar appearances were observed on heating ether in a sealed tube at 190°.

Andrews has observed that when liquid carbonic acid was heated to 31° C. the surface of demarcation between the liquid and the gas became fainter, lost its curvature, and gradually disappeared. The space was then occupied by a homogeneous fluid, which, when the pressure was suddenly diminished, or the temperature slightly lowered, exhibited a peculiar appearance of moving or flickering striæ throughout its whole mass. Above 30° no apparent liquefaction of carbonic anhydride, or separation into two distinct forms of matter, could be effected, even when the pressure of 400 atmospheres was applied. It would thus seem that there exists for every liquid a temperature, the *critical* temperature, at which no amount of pressure is capable of retaining it in the liquid form. It is not surprising, therefore, that mere pressure, however great, should fail to liquefy many of the bodies which usually exist as gases.

336. **Papin's digester.**—Papin, a French physician, appears to have been the first to study the effects of the productions of vapour in closed

vessels. The apparatus which bears his name consists of a cylindrical iron vessel (fig. 261), provided with a cover, which is firmly fastened down by the screw B. In order to close the vessel hermetically, sheet lead is placed between the edges of the cover and the vessel. At the bottom of a cylindrical cavity, which traverses the cylinder S, and the tubulure *o*, the cover is perforated by a small orifice in which there is a rod, *n*. This rod presses against a lever, A, movable at *a*, and the pressure may be regulated by means of a weight movable on this lever. The lever is so weighted, that when the tension in the interior is equal to 6 atmospheres, for example, the valve rises and the vapour escapes. The destruction of the apparatus is thus avoided, and the mechanism has hence received the name of *safety valve*. The digester is filled about two-thirds with water, and is heated on a furnace. The water may thus be raised to a temperature far above 100°, and the tension of the vapour increased to several atmospheres, according to the weight on the lever.

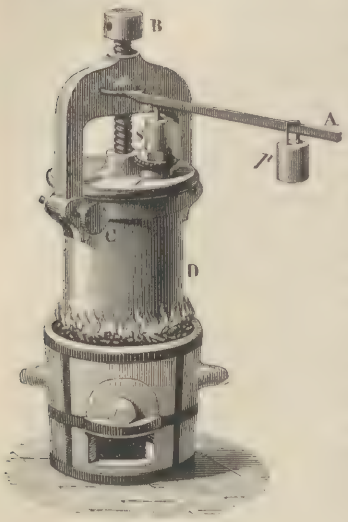


Fig. 261.

We have seen that water boils at much lower temperatures on high mountains (332); the temperature of water boiling in open vessels in such localities is not sufficient to soften animal fibre completely and extract the nutriment, and hence Papin's digester is used in the preparation of food.

Papin's digester is used in extracting gelatine. When bones are digested in this apparatus they are softened so that the gelatine which they contain is dissolved.

337. **Latent heat of vapour.**—As the temperature of a liquid remains constant during ebullition whatever be the source of heat (329), it follows that a considerable quantity of heat becomes absorbed in ebullition, the only effect of which is to transform the body from the liquid to the gaseous condition. And conversely when a saturated vapour passes into the state of liquid, it gives out an amount of heat.

These phenomena were first observed by Black, and he described them by saying that during vaporisation a quantity of sensible heat became latent, and that the latent heat again became free during condensation. The quantity of heat which a liquid must absorb in passing from the liquid to the gaseous state, and which it gives out in passing from the state of vapour to that of liquid, is spoken of as the *latent heat of evaporation.*

The analogy of these phenomena to those of fusion will be at once

seen; the modes of determining them will be described in the chapter on Calorimetry; but the following results, which have been obtained for the latent heats of evaporation of a few liquids, may be here given:—

Water	536	Bisulphide of carbon	87
Alcohol	208	Turpentine	74
Acetic acid	102	Bromine	46
Ether	90	Iodine	24

The meaning of these numbers is, in the case of water, for instance, that it requires as much heat to convert a pound of water from the state of liquid at the boiling point to that of vapour at the same temperature, as would raise a pound of water through 540 degrees, or 540 pounds of water through one degree: or that the conversion of one pound of vapour of alcohol at 78° into liquid alcohol of the same temperature would heat 208 pounds of water through *one* degree.

Watt, who investigated the subject, found that *the whole quantity of heat necessary to raise a given weight of water from zero to any temperature, and then to evaporate it entirely, is a constant quantity.* His experiments showed that this quantity is 640. Hence the lower the temperature the greater the latent heat, and, on the other hand, the higher the temperature the less the latent heat. The latent heat of the vapour of water evaporated at 100° would be 540, while at 50° it would be 590. At higher temperatures the latent heat of aqueous vapour would go on diminishing. Water evaporated under a pressure of 15 atmospheres at a temperature of 200°, would have a latent heat of 440, and if it could be evaporated at 640° it would have no latent heat at all.

Experiments by Southern and Creighton in 1803 led to a different conclusion: namely, that *the latent heat of evaporation is a constant quantity for all temperatures, and that the total quantity of heat necessary to evaporate water is the sensible heat plus this constant*, which they found in round numbers to be 540; consequently, to evaporate water at 100°, 640 thermal units (340) would be needed, while it would require $200 + 540 = 740$ thermal units to evaporate it at 200°.

Regnault, who examined this question with great care, arrived at results which differed from both these laws. He found that the *total quantity of heat necessary for the evaporation of water increases with the temperature*, and is not constant, as Watt had supposed. It is represented by the formula

$$Q = 606{\cdot}5 + 0{\cdot}305\ T,$$

in which Q is the total quantity of heat, and T the temperature of the water during evaporation, while the numbers are constant quantities. The total quantity of heat necessary to evaporate water at 100° is $606{\cdot}5 + (0{\cdot}305 \times 100) = 637$; at 120° it is 643; at 150° it is 651; and at 180° it is 661.

338. **Cold due to evaporation. Mercury frozen.**—Whatever be the temperature at which a vapour is produced, an absorption of heat always takes place. If, therefore, a liquid evaporates, and does not receive from without a quantity of heat equal to that which is expended in producing

the vapour, its temperature sinks, and the cooling is greater in proportion as the evaporation is more rapid.

Leslie succeeded in freezing water by means of rapid evaporation. Under the receiver of the air pump is placed a vessel containing strong sulphuric acid, and above it a thin metallic capsule (fig. 262) containing a small quantity of water. By exhausting the receiver the water begins to boil (332), and since the vapours are absorbed by the sulphuric acid as fast as they are formed, a rapid evaporation is produced, which quickly effects the freezing of the water.

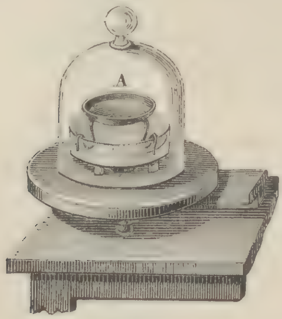


Fig. 262.

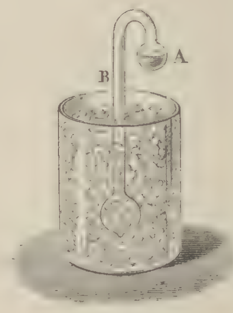


Fig. 263.

This experiment is best performed by using, instead of the thin metallic vessel, a watch-glass, coated with lampblack and resting on a cork. The advantage of this is twofold: firstly, the lampblack is a very bad conductor, and, secondly, it is not moistened by the liquid, which remains in the form of a globule not in contact with the glass. A small porous dish may advantageously be used.

The same result is obtained by means of Wollaston's *cryophorus* (fig. 263), which consists of a bent glass tube provided with a bulb at each end. The apparatus is prepared by introducing a small quantity of water, which is then boiled so as to expel all air. It is then hermetically sealed, so that on cooling it contains only water and the vapour of water.

The water being introduced into the bulb A, the other is immersed in a freezing mixture. The vapours in the tube are thus condensed; the water in A rapidly yields more. But this rapid production of vapour requires a large amount of heat, which is abstracted from the water in A, and its temperature is so much reduced that it freezes.

Carré has constructed an apparatus which is based upon Leslie's experiment, and by which considerable quantities of water may be frozen in a very short time. It consists of a horizontal brass cylinder, about fifteen inches in length and four in diameter, lined on the inside with an alloy of antimony and lead, so as to resist the action of strong sulphuric acid, with which it is about half filled. In the top of the cylinder, and at one end, is fitted a brass tube, bent twice at right angles, and constructed in such a manner that a flask containing water can be easily

fitted on air-tight. At the other end of the cylinder, also at the top, there is a somewhat wide upright tube B. This is connected with a simple air pump, specially devised for the purpose, and there is an arrangement so that the motion which works the pump works also a stirrer, which keeps the acid in continual agitation. A fresh surface is thus continually absorbing aqueous vapour; and as the space to be exhausted is small, and the pump very effective, soon after its working commences the water first boils and then freezes. These apparatus have been introduced for industrial purposes; and where there is a continual demand and use for dilute sulphuric acid, there seems no reason why this should not be an economical mode of making ice.

By using liquids more volatile than water, more particularly liquid sulphurous acid, which boils at $-10°$, a degree of cold is obtained sufficiently intense to freeze mercury. The experiment may be made by covering the bulb of a thermometer with cotton wool, and after having moistened it with liquid sulphurous acid, placing it under the receiver of the air pump. When a vacuum is produced the mercury is quickly frozen.

Thilorier, by directing a jet of liquid carbonic acid on the bulb of an alcohol thermometer, obtained a cold of $-100°$ without freezing the alcohol. We have already seen, however (310), that, with a mixture of solid carbonic acid, liquid protoxide of nitrogen and ether, M. Despretz obtained a sufficient degree of cold to reduce alcohol to the viscous state.

By means of the evaporation of bisulphide of carbon the formation of ice may be illustrated without the aid of an air pump. A little water is dropped on a small piece of wood, and a capsule of thin copper foil, containing bisulphide of carbon, is placed on the water. The evaporation of the bisulphide is accelerated by means of a pair of bellows, and after a few minutes the water freezes round the capsule, so that the latter adheres to the wood.

In like manner, if some water be placed in a test tube which is then dipped in a glass containing some ether, and a current of air be blown through the ether by means of a glass tube fitted to the nozzle of a pair of bellows, the rapid evaporation of the ether very soon freezes the water in the tube.

Richardson's apparatus for producing local anæsthesia also depends on the cold produced by the evaporation of ether.

The cold produced by evaporation is used in hot climates to cool water by means of *alcarrazas*. These are porous earthen vessels, through which water percolates, so that on the outside there is a continual evaporation which is accelerated when the vessels are placed in a current of air. For the same reason wine is cooled by wrapping the bottles in wet cloths and placing them in a draught.

In Harrison's method of making ice artificially, a steam engine is used to work an air pump, which produces a rapid evaporation of some ether, in which is immersed the vessel containing the water to be frozen. The apparatus is so constructed that the vaporised ether can be condensed and used again.

The cooling effect produced by a wind or draught does not necessarily arise from the wind being cooler, for it may, as shown by the thermometer, be actually warmer; but arises from the rapid evaporation it causes from the surface of the skin. We have the feeling of oppression, even at moderate temperatures, when we are in an atmosphere saturated by moisture in which no evaporation takes place.

339. **Carré's apparatus for freezing water.**—We have already seen that when any liquid is converted into vapour it absorbs a considerable quantity of sensible heat; this furnishes a source of cold which is the more abundant the more volatile the liquid and the greater its heat of vaporisation.

This property of liquids has been utilised by M. Carré, in freezing water by the distillation of ammonia. The apparatus consists of a cylindrical boiler C (figs. 264, 265) and of a slightly conical vessel A, which is

Fig. 264.

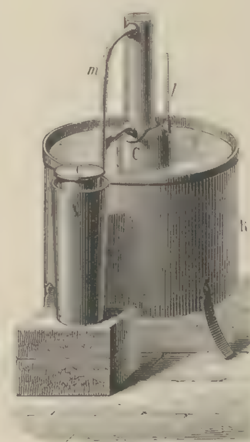


Fig. 265.

the *freezer*. These two vessels are connected by a tube *m*, and a brace *n* binds them firmly. They are made of strong galvanised plate, and can resist a pressure of seven atmospheres.

The boiler C, which holds about two gallons, is three parts filled with a strong solution of ammonia. In a tubulure in the upper part of the boiler some oil is placed, and in this a thermometer *t* indicating temperatures from 100° to 150°. The freezer A consists of two concentric envelopes, in such a manner that its centre being hollow, a metal vessel G, containing the water to be frozen, can be placed in this space. Hence only the annular space between the sides of the freezer is in communication with the boiler by means of the tube *m*. In the upper part of the freezer there is a small tubulure, which can be closed by a metal stopper, and by which the solution of ammonia is introduced.

The formation of ice comprehends two distinct operations. In the first, the boiler is placed in a furnace F, and the freezer in a bath of cold water of about 12°. The boiler being heated to 130° the ammoniacal gas dissolved in the water of the boiler is disengaged, and, in virtue of its own pressure, is liquefied in the freezer, along with about a tenth of its weight of water. This distillation of C towards A lasts about an hour and a quarter, and when it is finished the second operation commences; this consists in placing the boiler in the cold-water bath (fig. 265), and the freezer outside, care being taken to surround it with very dry flannel. The vessel G, about three-quarters full of water, is placed in the freezer. As the boiler cools, the ammoniacal gas with which it is filled is again dissolved; the pressure thus being diminished the ammonia which has been liquefied in it is converted into the gaseous form, and now distils from A towards C, to redissolve in the water which has remained in the boiler. During this distillation the ammonia which is rarefied absorbs a great quantity of heat, which is withdrawn from the vessel G and the water it contains. Hence it is that this water freezes. In order to have better contact between the sides of the vessel G and the freezer, alcohol is poured between them. In about an hour and a quarter a perfectly compact cylindrical block of ice can be taken from the vessel G.

This apparatus gives about four pounds of ice in an hour, at a price of about a farthing per pound: large continuously working apparatus have, however, been constructed, which produce as much as 800 pounds of ice in an hour.

LIQUEFACTION OF VAPOURS AND GASES.

340. **Liquefaction of vapours.**—The *liquefaction* or *condensation* of vapours is their passage from the aëriform to the liquid state. Condensation may be due to three causes—cooling, compression, or chemical affinity. For the first two causes the vapours must be saturated (320), while the latter produces the liquefaction of the most rarefied vapours. Thus, a large number of salts absorb and condense the aqueous vapour in the atmosphere, however small its quantity.

When vapours are condensed, their latent heat becomes free, that is, it affects the thermometer. This is readily seen when a current of steam at 100° is passed into a vessel of water at the ordinary temperature. The liquid becomes rapidly heated, and soon reaches 100°. The quantity of heat given up in liquefaction is equal to the quantity absorbed in producing the vapour.

341. **Distillation. Stills.**—*Distillation* is an operation by which a volatile liquid may be separated from substances which it holds in solution, or by which two liquids of different volatilities may be separated. The operation depends on the transformation of liquids into vapours by the action of heat, and on the condensation of these vapours by cooling.

The apparatus used in distillation is called a *still*. Its form may vary greatly, but consists essentially of three parts: 1st, the *body*, A (fig. 266), a copper vessel containing the liquid, the lower part of which fits in the

furnace : 2nd, the *head* B, which fits on the body, and from which a lateral tube, C, leads to, 3rd, *worm*, S, a long spiral tin or copper tube,

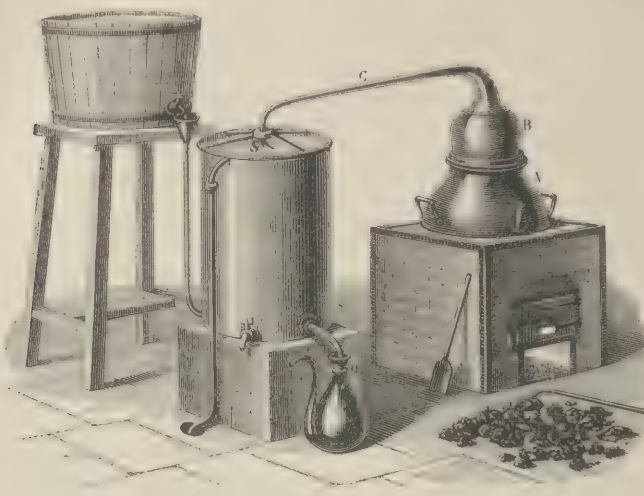


Fig. 266.

placed in a cistern kept constantly full of cold water. The object of the worm is to condense the vapour, by exposing a greater extent of cold surface.

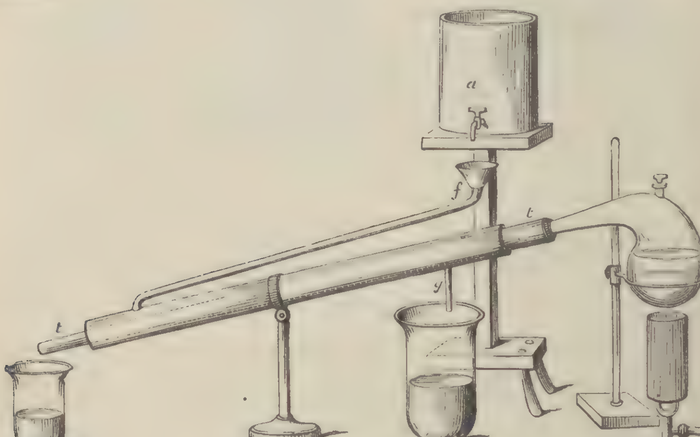


Fig. 267.

To free ordinary well water from the many impurities which it contains, it is placed in a still and heated. The vapours disengaged are condensed

in the worm, and the distilled water arising from the condensation is collected in the receiver, D. The vapours in condensing rapidly heat the water in the cistern, which must, therefore, be constantly renewed. For this purpose a continual supply of cold water passes into the bottom of the cistern, while the lighter heated water rises to the surface and escapes by a tube in the top of the cistern.

342. **Liebig's condenser.**—In distilling smaller quantities of liquids, or in taking the boiling point of a liquid, so as not to lose any of it, the apparatus known as *Liebig's condenser* is extremely useful. It consists of a glass tube, *tt*, fig. 267, about thirty inches long, fitted in a copper or tin tube by means of perforated corks. A constant supply of cold water from the vessel *a* passes into the space between the two tubes, being conveyed to the lower part of the condenser by a funnel and tube *f*, and flowing out from the upper part by the tube *g*. The liquid to be distilled is contained in a retort, the neck of which is placed in the tube; the condensed liquid drops quite cold into a vessel placed to receive it at the other extremity of the condensing tube.

343. **Apparatus for determining the alcoholic value of wines.**—One of the forms of this apparatus consists of a glass flask resting on a tripod, and heated by a spirit lamp (fig. 268). By means of a caout-

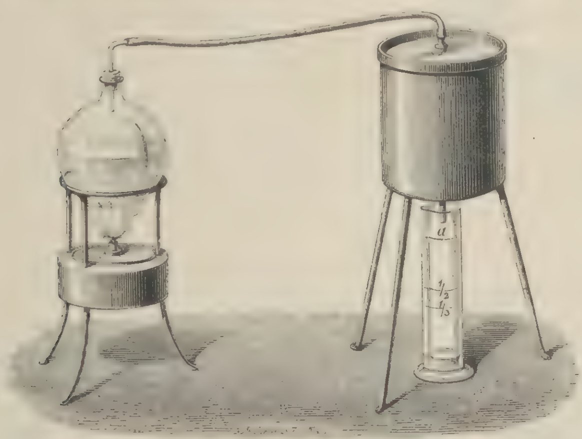


Fig. 268.

chouc tube this is connected with a serpentine placed in a copper vessel filled with cold water, and below which is a test-glass for collecting the distillate. On this are three divisions, one *a*, which measures the quantity of wine taken; the two others indicating one-half and one-third of this volume.

The test-glass is filled with the wine up to *a*, this is then poured into the flask, which, having been connected with the serpentine, the distillation is commenced. The liquid which distils over is a mixture of alcohol

and water; for ordinary wines, such as clarets and hocks, about one-third is distilled over, and for wines richer in spirit, such as sherries and ports, one-half must be distilled; experiment has shown that under these circumstances all the alcohol passes over in the distillate. The measure is then filled up with distilled water to *a*; this gives a mixture of alcohol and water of the same volume as the wine taken, free from all solid matters, such as sugar, colouring matter, and acid, but containing all the alcohol. The specific gravity of this distillate is then taken by means of an alcoholometer (120), and the number thus obtained corresponds to a certain strength of alcohol as indicated by the tables.

344. **Safety tube.**—In preparing gases and collecting them over mercury or water, it occasionally happens that these liquids rush back into the generating vessel, and destroy the operation. This arises from an excess of atmospheric pressure over the tension in the vessel. If a gas, sulphurous acid, for example, be generated in the flask *m* (fig. 269), and passed into water in the vessel A, as long as the gas is given off freely, its extension exceeds the atmospheric pressure and the weight of the column of water, *on*, so that the water in the vessel cannot rise in the tube, and absorption is impossible. But if the tension decreases either through the flask becoming cooled, or the gas being disengaged too slowly, the external pressure prevails, and when it exceeds the internal tension by more than the weight of the column of water *co*, the water rises into the flask and the operation is spoiled. This accident is prevented by means of *safety tubes*.

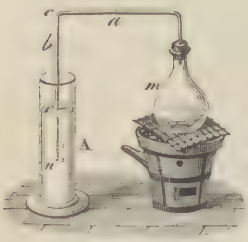


Fig. 269.

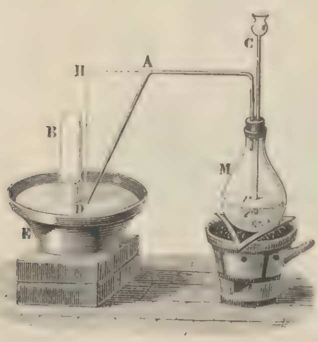


Fig. 270.

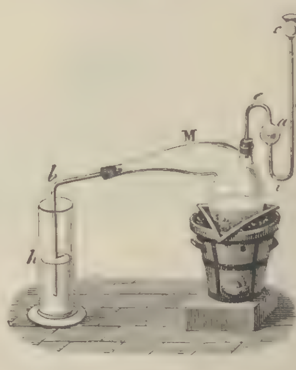


Fig. 271.

These are tubes which prevent absorption by allowing air to enter in proportion as the internal tension decreases. The simplest is a tube C*o* fig. 270, passing through the cork which closes the flask M, in which the

gas is generated and dipping in the liquid. When the tension of the gas diminishes in M, the atmospheric pressure on the water in the bath E causes it to rise to a certain height in the tube DA; but this pressure, acting also on the liquid in the tube C*o*, depresses it to the same extent, assuming that this liquid has the same density as the water in E. Now, as the distance *or* is less than the height DH, air enters by the aperture *o*, before the water in the bath can rise to A, and no absorption takes place.

Fig. 271 represents another kind of safety tube. It has a bulb *a*, containing a certain quantity of liquid, as does also *id*. When the tension of the gas in the retort M exceeds the atmospheric pressure, the level in the leg *id* rises higher than in the bulb, *a*; if the gas has the tension of one atmosphere, the level is the same in the tube as in the bulb. Lastly, if the tension of the gas is less than the atmospheric pressure the level sinks in the leg *di*; and, as care is taken that the height *ia* is less than *bh*, as soon as the air which enters through *c* reaches the curved part *i*, it raises the column *ia*, and passes into the retort before the water in the cylinder can reach *b*; the tension in the interior is then equal to the exterior pressure, and no absorption takes place.

345. **Liquefaction of gases.**—We have already seen that a saturated vapour, the temperature of which is constant, is liquefied by increasing the pressure, and that, the pressure remaining constant, it is brought into the liquid state by diminishing the temperature.

Unsaturated vapours behave in all respects like gases. And it is natural to suppose that what are ordinarily called *permanent gases* are really unsaturated vapours. For the gaseous form is accidental, and is not inherent in the nature of the substance. At ordinary temperatures sulphurous acid is a gas, while in countries near the poles it is a liquid; in temperate climates ether is a liquid, at a tropical heat it is a gas. And just as unsaturated vapours may be brought to the state of saturation and then liquefied by suitably diminishing the temperature or increasing the pressure, so by the same means gases may be liquefied. But as they are mostly very far removed from this state of saturation great cold and pressure are required. Some of them may indeed be liquefied either by cold or by pressure; for the majority, however, both processes must be simultaneously employed. Few gases can resist these combined actions, and probably those which have not yet been liquefied, hydrogen, oxygen, nitrogen, binoxide of nitrogen, and carbonic oxide, would become so if submitted to a sufficient degree of cold and pressure.

Fig. 272.

Faraday was the first to liquefy some of the gases. His method consists in enclosing in a bent glass tube (fig. 272) substances by whose chemical action the gas to be liquefied is produced and then sealing the shorter leg In proportion as the gas is disengaged its pressure increases, and it ulti-

mately liquefies and collects in the shorter leg, more especially if its condensation is assisted by placing the shorter leg in a freezing mixture. A small manometer may be placed in the apparatus to indicate the pressure.

Cyanogen gas is readily liquefied by heating cyanide of mercury in a bent tube of this description; and carbonic acid by heating bicarbonate of soda; other gases have been condensed by taking advantage of special reactions, the consideration of which belongs rather to chemistry than to physics. For example, chloride of silver absorbs about 200 times its volume of ammoniacal gas; when the compound thus formed is placed in a condensing tube and gently heated, while the shorter leg is immersed in a freezing mixture, a quantity of liquid ammoniacal gas speedily collects in the shorter leg.

346. **Apparatus to liquefy and solidify gases.**—Thilorier first constructed an apparatus by which considerable quantities of carbonic acid could be liquefied. Its principle is the same as that used by Faraday in working with glass tubes; the gas is generated in an iron cylinder, and passes through a metallic tube into another similar cylinder where it condenses. The use of this apparatus is not free from danger; many accidents have already happened with it, and it has been superseded by an apparatus constructed by Natterer, of Vienna, which is both convenient and safe.

A perspective view of the apparatus, as modified by M. Bianchi, is represented in fig. 274, and a section on a larger scale in fig. 273. It consists of a wrought-iron reservoir A, of something less than a quart capacity, which can resist a pressure of more than 600 atmospheres. A small force pump is screwed on the lower part of this reservoir. The piston rod *t* is moved by the crank rod E, which is worked by the handle M. As the compression of the gas and the friction of the piston produce a considerable disengagement of heat the reservoir A is surrounded by a copper vessel in which ice of a freezing mixture is placed. The water arising from the melting of the ice passes by a tube, *m*, into a cylindrical copper case C, which surrounds the force pump, from whence it escapes through the tube *n*, and the stopcock *o*. The whole arrangement rests on an iron frame, PQ.

The gas to be liquefied is previously collected in air-tight bags, R, from whence it passes into a bottle, V, containing some suitable drying substance; it then passes into the condensing pump through the vulcanised india rubber tube H. After the apparatus has been worked for some time the reservoir A can be unscrewed from the pump without any escape of the liquid, for it is closed below by a valve S (fig. 273). In order to collect some of the liquid gas the reservoir is inverted and on turning the stopcock *r*, the liquid escapes by a small tubulure *x*.

When carbonic acid has been liquefied, and is allowed to escape into the air, a portion only of the liquid volatilises, in consequence of the heat absorbed by this evaporation; the rest is so much cooled as to solidify in white flakes like snow or anhydrous phosphoric acid.

Solid carbonic acid evaporates very slowly. By means of an alcohol thermometer its temperature has been found to be about $-90°$. A small

quantity placed on the hand does not produce the sensation of such great cold as might be expected. This arises from the imperfect contact. But if the solid be mixed with ether the cold produced is so intense that when a little is placed on the skin all the effects of a severe burn are produced. A mixture of these two substances solidifies four times its weight of mercury in a few minutes. When a tube containing liquid carbonic acid is

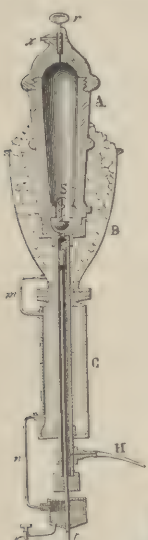


Fig. 273.

Fig. 274.

placed in this mixture, the liquid becomes solid, and looks like a transparent piece of ice.

The most remarkable liquefaction obtained by this apparatus is that of protoxide of nitrogen. The gas once liquefied only evaporates slowly, and produces a temperature of 88° below zero. Mercury placed in it in small quantities instantly solidifies. The same is the case with water; it must be added drop by drop, otherwise its latent heat being much greater than that of mercury, the heat given up by the water in solidifying would be sufficient to cause an explosion of the protoxide of nitrogen.

Protroxide of nitrogen is readily decomposed by heat, and has the property of supporting the combustion of bodies with almost as much brilliancy as oxygen ; and even at low temperatures it preserves this property. When a piece of incandescent charcoal is thrown on liquid protoxide of nitrogen it continues to burn with a brilliant light.

The cold produced by the evaporation of ether has been used by MM. Loir and Drion in the liquefaction of gases. By passing a current of air from a blowpipe bellows through several tubes into a few ounces of ether, a temperature of $-34°$ C. can be reached in five or six minutes, and may be kept up for fifteen or twenty minutes. By evaporating liquid sulphurous acid in the same manner a greater degree of cold, $-50°$C., is obtained. At this temperature ammoniacal gas may be liquefied. By rapidly evaporating liquid ammonia under the air pump, in the presence of sulphuric acid, a temperature of $-87°$ is attained, which is found sufficient to liquefy carbonic acid under the ordinary pressure of the atmosphere.

By means of a bath of ether and of solid carbonic acid, and by using very high pressures, Andrews succeeded in reducing air to $\frac{1}{675}$ of its bulk, oxygen to $\frac{1}{554}$, hydrogen to $\frac{1}{500}$, carbonic oxide to $\frac{1}{275}$, and nitric oxide to $\frac{1}{680}$ of its original volume, but without producing liquefaction. Hydrogen and carbonic oxide departed less from Boyle's law than oxygen and nitric oxide.

MIXTURES OF GASES AND VAPOURS.

347. **Laws of the mixture of gases and vapours.**—Every mixture of a gas and a vapour obeys the following two laws :—

I. *The tension, and, consequently, the quantity of vapour which saturates a given space are the same for the same temperature, whether this space contains a gas or is a vacuum.*

II. *The tension of the mixture of a gas and a vapour is equal to the sum of the tensions which each would possess if it occupied the same space alone.*

These are known as *Dalton's laws*, from their discoverer, and are demonstrated by the following apparatus, which was invented by Gay-Lussac :—It consists of a glass tube A (fig. 275), to which two stopcocks, *b* and *d*, are cemented. The lower stopcock is provided with a tubulure, which connects the tube A with a tube B of smaller diameter. A scale between the two tubes serves to measure the heights of the mercurial columns in these tubes.

The tube A is filled with mercury, and the stopcocks *b* and *d* are closed. A glass globe, M, filled with dry air or any other gas is screwed on by means of a stopcock in the place of the funnel C. All three stopcocks are then opened, and a little mercury is allowed to escape, which is replaced by the dry air of the globe. The stopcocks are then closed, and as the air in the tube expands on leaving the globe the pressure on it is less than that of the atmosphere. Mercury is accordingly poured into the tube B until it is at the same level in both tubes. The globe is then

removed, and replaced by a funnel C, provided with a stopcock *a* of a peculiar construction. It is not perforated, but has a small cavity, as represented in *n*, on the left of the figure. Some of the liquid to be vaporised is poured into C, and the height of the mercury, *k*, having been noted, the stopcock *b* is opened, and *a* turned, so that its cavity becomes filled with liquid; being again turned, the liquid enters the space A and vaporises. The liquid is allowed to fall drop by drop until the air in the tube is saturated, which is the case when the level *k* of the mercury ceases to sink (319).

As the tension of the vapour produced in the space A is added to that of the air already present, the total volume of gas is increased. It may easily be restored to its original volume by pouring mercury into B. When the mercury in the large tube has been raised to the level *k*, there is a difference, B*o*, in the level of the mercury in the two tubes, which obviously represents the tension of the vapour; for as the air has resumed its original volume, its tension has not changed. Now if a few drops of the same liquid be passed into the vacuum of a barometric tube a depression exactly equal to B*o* is produced, which proves that, for the same temperature, the tension of a saturated vapour is the same in a gas as in a vacuum; from which it is concluded that at the same temperature the quantity of vapour is also the same.

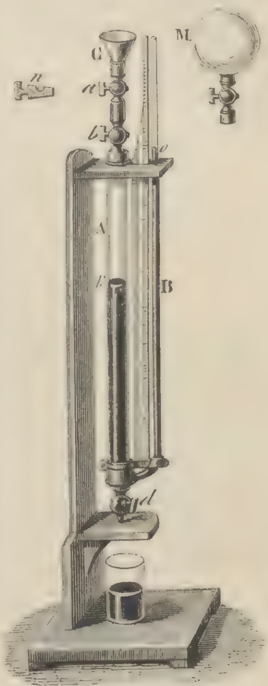


Fig. 275.

The second law is likewise proved by this experiment, for when the mercury has regained its level, the mixture supports the atmospheric pressure on the top of the column B, in addition to the weight of the column of mercury B*o*. But of these two pressures, one represents the tension of the dry air, and the other the tension of the vapour. The second law is, moreover, a necessary consequence of the first.

Experiments can only be made with this apparatus at ordinary temperatures: but M. Regnault, by means of an apparatus which can be used at different temperatures, has investigated the tensions of the vapours of water, ether, bisulphide of carbon, and benzole, both in vacuo and in air. He has found that the tension in air is less than it is in vacuo, but the differences are so small as not to invalidate Dalton's law. M. Regnault is even inclined to consider this law as theoretically true, attributing the differences which he observed to the hygroscopic properties of the sides of the tube.

348. **Problems on mixtures of gases and vapours.**—I. A volume of

dry air V, at the pressure H, being given, what will be its volume V′, when it is saturated with vapour, the temperature and the pressure remaining the same?

If F be the elastic force of the vapour which saturates the air, the latter, in the mixture, only supports a pressure equal to H – F (347). But by Boyle and Mariotte's law the volumes V and V′ are inversely as their pressures, consequently

$$\frac{V'}{V} = \frac{H}{H-F}, \text{ whence } V' = \frac{VH}{H-F}$$

II. Let V be a given volume of saturated air at the pressure H, and the temperature t, what will be its volume V″, also saturated, at the pressure H′, and the temperature t'?

If f be the maximum tension of aqueous vapour at $t°$, and f' its maximum tension at $t'°$, the air alone in each of the mixtures V and V′ will be respectively under the pressures $H-f$ and $H'-f'$; consequently, assuming first that the temperature is constant, we obtain

$$\frac{V'}{V} = \frac{H-f}{H'-f'}$$

But as the volumes V′ and V of air, at the temperatures t' and t, are in the ratio of $1 + at'$ to $1 + at$, a being the coefficient of the expansion of air, the equation becomes

$$\frac{V'}{V} = \frac{H-f}{H' \times f'} \times \frac{1 + at'}{1 + at}$$

III. What is the weight P of a volume of air V, saturated with aqueous vapour at the temperature t, and pressure H?

If we call F the maximum tension of the vapour at $t°$, the tension of the air alone will be H – F, and the problem reduces itself to finding: 1st, the weight of V cubic inches of dry air at t, and under the pressure H – F; and 2nd, the weight of V cubic inches of saturated vapour at $t°$ under the pressure.

To solve the first part of the problem we know that a cubic inch of dry air at 0° and the pressure 760 millimeters weighs 0·31 grains, and that at $t°$, and the pressure H – F, it weighs $\frac{0·31\ (H-F)}{(1+at)\ 760}$ (300), consequently V cubic inches of dry air weigh

$$\frac{0·31\ (H-F)\ V}{(1+at)\ 760} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

To obtain the weight of the vapour, the weight of the same volume of dry air at the same temperature and pressure must be sought, and this is to be multiplied by the relative density of the vapour. Now as V cubic inches of dry air at $t°$, and the pressure F, weigh $\frac{0·31 \times VF}{(1+at)\ 760}$ V cubic inches of aqueous vapour, whose density is $\frac{5}{8}$ of that of air (351), weigh

$$\frac{0·31 \times VF}{(1+at)\ 760} \times \frac{5}{8} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and as the weight P is equal to the sum of the weights (1) and (2) we have

$$P = \frac{0{\cdot}31 \times V\,(H - F)}{(1 + \alpha t)\,760} + \left[\frac{0{\cdot}31 \times VF}{(1 + \alpha t)\,760} \times \frac{5}{8}\right] = \frac{0{\cdot}31 \times VF}{(1 + \alpha t)\,760}\,(H - \tfrac{3}{8}F).$$

SPHEROIDAL CONDITION.

349. **Leidenfrost's phenomenon.—Boutigny's experiments.**—When liquids are thrown upon incandescent metallic surfaces they present remarkable phenomena, which were first observed by Leidenfrost a century ago, and have been named after their discoverer. They have since then been studied by other physicists, and more especially by M. Boutigny, to whom our present knowledge of the subject is mainly due.

When a tolerably thick silver or platinum dish is heated to redness, and a little water, previously warmed, dropped into the dish by means of a pipette, the liquid does not spread itself out on the dish. and does not moisten it, as it would at the ordinary temperature, but assumes the form of a flattened globule, which fact M. Boutigny expresses by saying that it has passed into the *spheroidal state.* It rotates rapidly round on the bottom of the dish, taking sometimes the form of a star, and not only does it not boil, but its evaporation is only about one-fiftieth as rapid as if it boiled. As the dish cools, a point is reached at which it is not hot enough to keep the water in the spheroidal state; it is accordingly moistened by the liquid, and a violent ebullition suddenly ensues.

All volatile liquids can assume the spheroidal condition; the lowest temperature at which it can be produced varies with each liquid, and is more elevated the higher the boiling point of the liquid. For water, the dish must have at least a temperature of 200°; for alcohol, 134°; and for ether, 61°.

The temperature of a liquid in the spheroidal state is always below its boiling point. This temperature has been measured by M. Boutigny by means of a very delicate thermometer; but his method is not free from objections, and it is probable that the temperatures he obtained were too high. He found that of water to be 95°; alcohol, 75°; ether, 34°; and liquid sulphurous acid, $-11°$. But the temperature of the vapour which is disengaged appears to be as high as that of the vessel itself.

This property of liquids in the spheroidal state remaining below their boiling point has been applied by M. Boutigny in a remarkable experiment, that of freezing water in a red-hot crucible. He heated a platinum dish to bright redness, and placed a small quantity of liquid sulphurous acid in it. It immediately assumed the spheroidal condition, and its evaporation was remarkably slow. Its temperature, as has been stated, was about $-11°$, and when a small quantity of water was added it immediately solidified, and a small piece of ice could be thrown out of the red-hot crucible. In a similar manner Faraday, by means of a mixture of solid carbonic acid and ether, succeeded in freezing mercury in a red-hot crucible.

In the spheroidal state the liquid is not in contact with the vessel. M.

Boutigny proved this by heating a silver plate placed in a horizontal position, and dropping on it a little dark coloured water. The liquid assumed the spheroidal condition, and the flame of a candle placed at some distance could be distinctly seen between the drop and the plate. If a plate perforated by several fine holes be heated, a liquid will assume the spheroidal state when projected upon it. This is also the case with a flat helix of platinum wire pressed into a slightly concave shape. An experiment of another class, due to Mr. A. H. Church, also illustrates the same fact. A polished silver dish is made red hot, and a few drops of a solution of sulphide of sodium are projected on it. The liquid passes into the spheroidal condition, and the silver undergoes no alteration. But if the dish is allowed to cool, the liquid instantly moistens it, producing a dark spot, due to the formation of sulphide of silver. In like manner nitric acid assumes the spheroidal state when projected on a heated silver plate, and does not attack the metal so long as the plate remains hot.

An analogous phenomenon is observed when potassium is placed on water. Hydrogen is liberated, and burns with a yellow flame ; hydrate of potassium, which is formed at the same time, floats on the surface without touching it, owing to its high temperature. In a short time it cools down, and the globule coming in contact with water bursts with an explosion.

Similarly liquids may be made to roll upon liquids, and solid bodies which vaporise without becoming liquid also assume a condition analogous to the spheroidal state of liquids when they are placed on a surface whose temperature is sufficiently high to vaporise them rapidly. This is seen when a piece of carbonate of ammonium is placed in a red-hot platinum crucible.

The phenomena of the spheroidal state seem to prove that the liquid globule rests upon a sort of cushion of its own vapour, produced by the heat radiated from the hot surface against its under-side. As fast as this vapour escapes from under the globule, its place is supplied by a fresh quantity formed in the same way, so that the globule is constantly buoyed up by it, and does not come in actual contact with the heated surface. When, however, the temperature of the latter falls, the formation of vapour at the under-surface becomes less and less rapid, until at length it is not sufficient to prevent the globule touching the hot metal or liquid on which it rests. As soon as contact occurs heat is rapidly imparted to the globule, it enters into ebullition, and quickly boils away.

These experiments on the spheroidal state explain the fact that the hand may be dipped into melted lead, or even melted iron, without injury. It is necessary that the liquid metal be heated greatly above its solidifying point. Usually the natural moisture of the hand is sufficient, but it is better to wipe it with a damp cloth. In consequence of the great heat, the hand becomes covered with a layer of speroidal fluid, which prevents the contact of the metal with the hand. Radiant heat alone operates, and this is principally expended in forming aqueous vapour on the surface of the hand. If the hand is immersed in boiling

water, the water adheres to the flesh, and consequently a scald is produced.

The tales of ordeals by fire during the middle ages, of men who could run barefooted over red-hot iron without being injured, are possibly true in some cases, and would find a ready explanation in the preceding phenomena.

DENSITY OF VAPOURS.

350. **Gay-Lussac's method.**—The *density of a vapour* is the relation between the weight of a given volume of this vapour and of that of the same volume of air at the same temperature and pressure.

Two methods principally are used in determining the density of vapours: Gay-Lussac's, which serves for liquids which boil at about 100°, and Dumas', which can be used up to 350°.

Figure 276 represents the apparatus used by Gay-Lussac. It consists of an iron vessel containing mercury, in which there is a glass cylinder, M. This is filled with water or oil, and the temperature is indicated by the thermometer, T. In the interior of the cylinder is a graduated glass jar, C, which, at first, is filled with mercury.

The liquid whose vapour density is to be determined is placed in a small bulb, A, represented on the left of the figure. The bulb is then sealed and weighed; the weight of the liquid taken is obviously the weight of the bulb when filled, minus its weight while empty. The bulb is then introduced into the jar C, and the liquid in M gradually heated somewhat higher than the boiling point of the liquid in the bulb. In consequence of the expansion of this liquid the bulb breaks, and the liquid becoming converted into vapour the mercury is depressed, as represented in the figure. The bulb must be so small that all the liquid in it is vaporised. The volume of the vapour is given by the graduation on the jar. Its temperature is indicated by the thermometer T, and the pressure is indicated by the difference between the height of the barometer at the time of the observation, and the height of the column of mercury in the gas jar. It is only necessary then to calculate the weight of a volume of air equal to that of the vapour under the same conditions of temperature and pressure. The quotient, obtained by dividing the weight of the vapour by that of the air, gives the required density of the vapour.

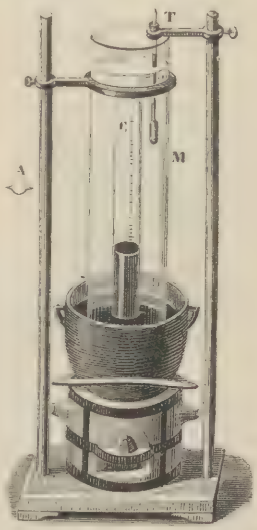


Fig. 276.

Let p be the weight of the vapour in grains, v its volume in cubic inches, and t its temperature; if H be the height of the barometer, and h that of the mercury in the gas jar, the pressure on the vapour will be $H - h$.

It is required to find the weight p' of a volume of air v, at the temperature t, and under a pressure $H-h$. At zero, under the pressure 760 millimeters, a cubic inch of air weighs 0·31 grains; consequently, under the same conditions, v cubic inches will weigh 0·31 v grains. And therefore the weight of v cubic inches of air, at $t°$ and the pressure 760 millimeters is

$$\frac{0{\cdot}31v}{1+\alpha t} \text{ grains [300, prob. ii.].}$$

As the weight of a volume of air is proportional to the pressure, the above weight may be reduced to the pressure $H-h$ by multiplying by $\frac{H-h}{760}$, which gives

$$\frac{0{\cdot}31\, v\,(H-h)}{(1+\alpha t)\,760}$$

for the weight p' of the volume of air v, at the pressure $H-h$, at $t°$. Consequently, for the desired density we have

$$D=\frac{p}{p'}=\frac{p\,(1+\alpha t)\,760}{0{\cdot}31\,v\,(H-h)}$$

351. **Dumas' method.**—The method just described cannot be applied to liquids whose boiling point exceeds 150° or 160°. In order to raise the oil in the cylinder to this temperature it would be necessary to heat the mercury to such a degree that the mercurial vapours would be dangerous to the operator. And, moreover, the tension of the mercurial vapours in the graduated jar would increase the tension of the vapour of the liquid, and so far vitiate the result.

Fig. 277.

The following method, devised by M. Dumas, can be used up to the temperature at which glass begins to soften; that is, about 400°. A glass globe is used with the neck drawn out to a fine point (fig. 277). The globe, having been dried externally and internally, is weighed, the temperature t and barometric height h being noted. This weight W is the weight of the glass G in addition to p, the weight of the air it contains. The globe is then gently warmed, and its point immersed in the liquid whose vapour density is to be determined: on cooling, the air contracts, and a quantity of liquid enters the globe. The globe is then immersed in a bath, either of oil or fusible metal, according to the temperature to which it is to be raised. In order to keep the globe in a vertical position a metallic support, on which a movable rod slides, is fixed on the side of the vessel. This rod has two rings, between which the globe is placed, as shown in the figure. There is another rod, to which a weight thermometer, D, is attached.

The globe and thermometer having been immersed in the bath, the latter is heated until slightly above the boiling point of the liquid in the globe. The vapour which passes out by the point expels all the air in the interior. When the jet of vapour ceases, which is the case when all the liquid has been converted into vapour, the point of the globe is hermetically sealed, the temperature of the bath t', and the barometric height h', being noted. When the globe is cooled, it is carefully cleaned and again weighed. This weight, W′, is that of the glass, G, plus p', the weight of the vapour which fills the globe at the temperature t' and pressure h', or $W' = G + p$. To obtain the weight of the glass alone, the weight p of air must be known, which is determined in the following manner: The point of the globe is placed under mercury and the extremity broken off with a small pair of pinchers: the vapour being condensed, a vacuum is produced, and mercury rushes up, completely filling the globe, if, in the experiment, all the air has been completely. expelled. The mercury is then poured into a carefully graduated measure, which gives the volume of the globe. From this result, the volume of the globe at the temperature t' may be easily calculated and consequently the volume of the vapour. From this determination of the volume of the globe the weight p of the air at the temperature t and pressure h is readily calculated, and this result subtracted from W gives G, the weight of the glass. Now the weight of the vapour p' is $W' - G$. We now know the weight p' of a given volume of vapour at the temperature t' and pressure h', and it is only necessary to calculate the weight p'' of the same volume of air under the same conditions, which is easily accomplished. The quotient $\frac{p'}{p''}$ is the required density of the vapour.

Densities of Vapours.

Air	1·0000	Vapour of phosphorus	4·3256
Vapour of water	0·6235	„ turpentine	5·0130
„ alcohol	1·6138	„ sulphur	6·6542
„ ether	2·5860	„ mercury	6·9760
„ bisulphide of carbon	2·6447	„ iodine	8·7160

The density of aqueous vapour, when a space is saturated with it, is at all temperatures $\frac{5}{8}$, or, more accurately, 0·6225, of the density of air at the same temperature and pressure.

352. **Deville and Troost's method.**—Deville and Troost have modified Dumas' method so that it can be used for determining the vapour density of liquids with very high boiling points. The globe is heated in an iron cylinder in the vapour of mercury or of sulphur, the temperatures of which are constant respectively at 350° and 460°. In other respects the determination is the same as in Dumas' method.

For determinations at higher temperatures, Deville and Troost have employed the vapour of zinc, the temperature of which is 1040°. As glass vessels are softened by this heat, they use porcelain globes with finely drawn out necks, which are sealed by means of the oxyhydrogen flame.

353. **Relation between the volume of a liquid and that of its vapour.**—The density of vapour being known, we can readily calculate the ratio between the volume of a vapour in the saturated state at a given temperature, and that of its liquid at zero. We may take, as an example, the relation between water at zero and steam at 100°.

The ratio between the weights of equal volumes of air at zero, and the normal barometric pressure, and of water under the same circumstance is as 1 : 773. But from what has been already said (300), the density of air at zero is to its density at 100° as $1 + \alpha t : 1$. Hence the ratio between the weights of equal volumes of air at 100° and water at 0°, is $\frac{1}{1 + 0{\cdot}003665 \times 100} : 773$, or 0·73178 : 773.

Now from the above table the density of steam at 100° C., and the normal pressure, compared with that of air under the same circumstances, is as 0·6225 : 1. Hence the ratio between the weights of equal volumes of steam at 100°, and water at 0°, is

$$0{\cdot}73178 \times 0{\cdot}6225 : 773, \text{ or } 0{\cdot}4555 : 773 \text{ or } 1 : 1698.$$

Therefore, as the volumes of bodies are inversely as their densities, one volume of water at zero expands into 1698 volumes of steam at 100° C. The practical rule that a cubic inch of water yields a cubic foot of steam, though not quite accurate, expresses the relation in a convenient form.

CHAPTER VI.

HYGROMETRY.

354. **Object of hygrometry.**—The object of *hygrometry* is to determine the quantity of aqueous vapour contained in a given volume of air. This quantity is very variable; but the atmosphere is never completely saturated with vapour, at any rate, in our climates. Nor is it ever completely dry; for if *hygrometric substances*, that is to say, substances with a great affinity for water, such as chloride of calcium, sulphuric acid, etc., be at any time exposed to the air, they absorb aqueous vapour.

355. **Hygrometric state.**—As in general the air is never saturated, the ratio of the quantity of aqueous vapour actually present in the atmosphere, to that which it would contain if it were saturated, the temperature remaining the same, is called the *hygrometric state*, or *degree of saturation.*

The degree of moisture does not depend on the absolute quantity of aqueous vapour present in the air, but on the greater or less distance of the air from its point of saturation. When the air is cold it may be moist with very little vapour, and, on the contrary, when it is warm, very dry, even with a large quantity of vapour. In summer the air usually contains more aqueous vapour than in winter, notwithstanding which it

is less moist, because, the temperature being higher, the vapour is farther from its point of saturation. When a room is warmed, the quantity of moisture is not diminished, but the humidity of the air is lessened, because its point of saturation is raised. The air may thus become so dry as to be injurious to the health, and it is hence usual to place vessels of water on the stoves used for heating.

As Boyle's law applies to nonsaturated vapours as well as to gases (320), it follows that, with the same temperature and volume, the weight of vapour in a nonsaturated space increases with the pressure and therefore with the tension of the vapour itself. Instead, therefore, of the ratio of the quantities of vapour, that of the corresponding tensions may be substituted, and it may be said that the hygrometric state is *the ratio of the tension of the aqueous vapour which the air actually contains, to the tension of the vapour which it would contain at the same temperature if it were saturated.*

If f is the actual tension of aqueous vapour in the air, and F that of saturated vapour at the same temperature, and E the hygrometric state, we have $E = \frac{f}{F}$; whence $f = F \times E$.

As a consequence of this second definition, it is important to notice that the temperature having varied, the air may contain the same quantity of vapour and yet not have the same hygrometric state. For, when the temperature rises, the tension of the vapour which the air would contain if saturated increases more rapidly than the tension of the vapour actually present in the atmosphere, and hence the ratio between the two forces, that is to say, the hygrometric state, becomes smaller.

It will presently be explained (363) how the weight of the vapour contained in a given volume of air may be deduced from the hygrometric state.

356. **Different kinds of hygrometers.**—*Hygrometers* are instruments for measuring the hygrometric state of the air. There are numerous varieties of them—chemical hygrometers, condensing hygrometers and psychrometers.

357. **Chemical hygrometer.**—The method of the chemical hygrometer consists in passing a known volume of air over a substance which readily absorbs moisture—chloride of calcium, for instance. The substance having been weighed before the passage of the air, and then afterwards, the increase in weight represents the amount of aqueous vapour present in the air. By means of the apparatus represented in fig. 278, it is possible to examine any given volume. Two brass reservoirs A and B, of the same size and construction, act alternately as aspirators, by being fixed to the same axis, about which they can turn. They are connected by a central tubulure, and by means of two tubulures in the axis the lower reservoir is always in connection with the atmosphere, while the upper one, by means of a caoutchouc tube, is connected with two tubes M and N, filled either with chloride of calcium, or with pumice stone impregnated with sulphuric acid. The first absorbs the vapour in the air

drawn through, while the other, M, stops any vapour which might diffuse from the reservoirs to the tube N.

The lower reservoir being full of water, and the upper one of air, the apparatus is inverted so that the liquid flows slowly from A to B. A vacuum being formed in A, air enters by the tubes NM, in the first of which all the vapour is absorbed. When all the water has run into B it is turned; the same flow recommences, and the same volume of air is

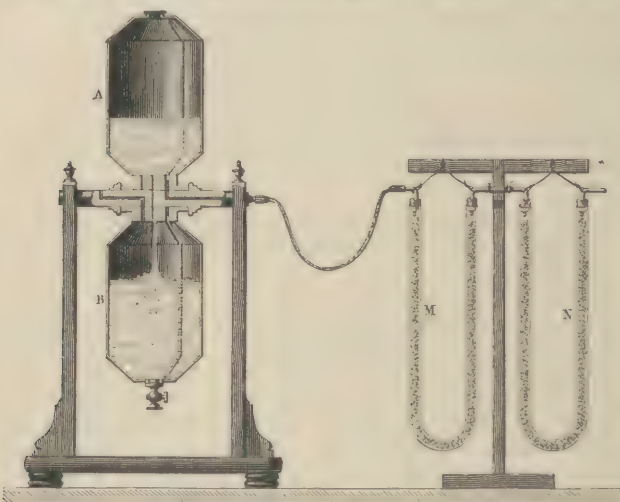


Fig. 278.

drawn through the tube N. Thus, if each reservoir holds a gallon, for example, and the apparatus has been turned five times, 6 gallons of air have traversed the tube N, and have been dried. If then, before the experiment, the tube with its contents has been weighed, the increase in weight gives the weight of aqueous vapour present in 6 gallons of air at the time of the experiment.

358. **Condensing hygrometers.**—When a body gradually cools in a moist atmosphere, as, for instance, when a lump of ice is placed in water contained in a polished metal vessel, the layer of air in immediate contact with it cools also, and a point is ultimately reached at which the vapour present is just sufficient to saturate the air: the least diminution of temperature then causes a precipitation of moisture on the vessel in the form of dew. When the temperature rises again, the dew disappears. The mean of these two temperatures is taken as the *dew point*, and the object of condensing hygrometers is to observe this point. Daniell's and Regnault's hygrometers belong to this class.

359. **Daniell's hygrometer.**—This consists of two glass bulbs at the extremities of a glass tube bent twice (fig. 279). The bulb A is two-thirds full of ether, and a very delicate thermometer plunges in it; the rest of

the space contains nothing but the vapour of ether, the ether having been boiled before the bulb B was sealed. The bulb B is covered with muslin, and ether is dropped upon it. The ether in evaporating cools the bulb, and the vapour contained in it is condensed. The internal tension being thus diminished, the ether in A forms vapours which condense in the other bulb B. In proportion as the liquid distils from the lower to the upper bulb, the ether becomes cooler, and ultimately the temperature of the air in immediate contact with A sinks to that point at which its vapour is more than sufficient to saturate it, and it is, accordingly, deposited on the outside as a ring of dew corresponding to the surface of the ether. The temperature of this point is noted by means of the thermometer in the inside. The addition of ether to the bulb B is then discontinued, the temperature of A rises, and the temperature at which the dew disappears is noted. In order to render the deposition of dew more perceptible, the bulb A is made of black glass.

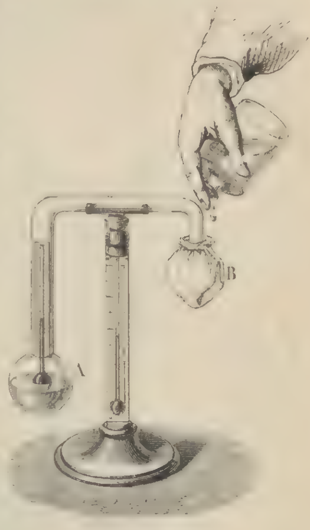


Fig. 279.

These two points having been determined, their mean is taken as that of the dew point. The temperature of the air at the time of the experiment is indicated by the thermometer on the stem. The tension *f*, corresponding to the temperature of the dew point, is then found in the table of tensions (324). This tension is exactly that of the vapour present in the air at the time of the experiment. The tension F of vapour saturated at the temperature of the atmosphere is found by means of the same table; the quotient obtained by dividing *f* by F, represents the hygrometric state of the air (355). For, instance, the temperature of the air being 50°, suppose the dew point is 5°. From the table the corresponding tensions are $f = 6{\cdot}534$ millimeters, and $F = 12{\cdot}699$ millimeters, which gives 0·514 for the ratio of *f* to F, or the hygrometric state.

There are many sources of error in Daniell's hygrometer. The principal are: 1st, that as the evaporation in the bulb A only cools the liquid on the surface, the thermometer dipping on it does not exactly give the dew point; 2nd, that the observer standing near the instrument modifies the hygrometric state of the surrounding air, as well as its temperature; the cold ether vapour too flowing from the upper bulb may cause inaccuracy.

360. **Regnault's hygrometer.**—Regnault's hygrometer is free from the sources of error incidental to the use of Daniell's. It consists of two very thin polished silver thimbles 1·75 inch in height, and 0·75 inch in diameter (fig. 280). In these are fixed two glass tubes, D and E, in each

of which is a thermometer. A bent tube, A, open at both ends, passes through the cork of the tube D, and reaches nearly to the bottom of the thimble. There is a tubulure on the side of D, fitting in a brass tube which forms a support for the apparatus. The end of this tube is connected with an aspirator G. The tube E is not connected with the aspirator; its thermometer simply indicates the temperature of the atmosphere.

The tube D is then half filled with ether, and the stopcock of the aspirator opened. The water contained in it runs out, and just as much

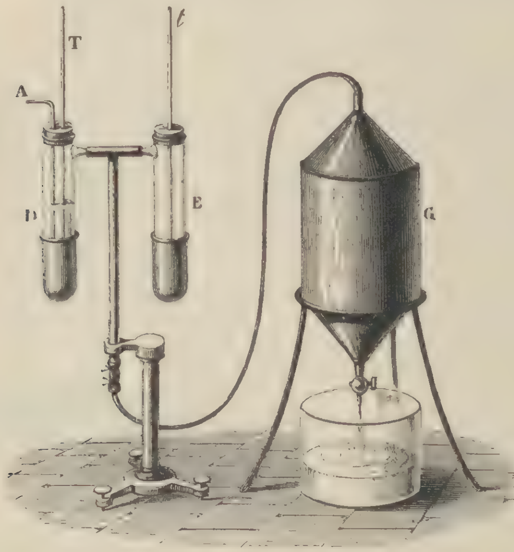


Fig. 280.

air enters through the tube A, bubbling through the ether, and causing it to evaporate. This evaporation produces a diminution of temperature, so that dew is deposited on the silver just as on the bulb in Daniell's hygrometer, the thermometer T is then instantly to be read, and the stream from the aspirator stopped. The dew will soon disappear again, and the thermometer T is again to be read; the mean of the two readings is taken: the thermometer *t* gives the corresponding temperature of the air, and hence there are all the elements necessary for calculating the hygrometric state.

As in this instrument, all the ether is at the same temperature in consequence of the agitation, and the temperatures are read off at a distance by means of a telescope, the sources of error in Daniell's hygrometer are avoided.

A much simpler form of the apparatus may be constructed out of a

common test tube containing a depth of $1\frac{1}{2}$ inch of ether. The tube is provided with a loosely fitting cork in which is a delicate thermometer and a narrow bent tube dipping in the ether. On blowing through the ether, by a caoutchouc tube of considerable length, a diminution of temperature is caused, and dew is ultimately deposited on the glass; after a little practice the whole process can be conducted almost as well as in Regnault's complete instrument. The temperature of the air is indicated by a free thermometer.

361. **Psychrometer. Wet bulb hygrometer.**—A moist body evaporates in the air more rapidly in proportion as the air is drier, and in consequence of this evaporation the temperature of the body sinks. The *psychrometer*, or *wet bulb hygrometer*, is based on this principle, the application of which, to this purpose, was first suggested by Leslie. The form usually adopted in this country is due to Mason. It consists of two delicate thermometers placed on a wooden stand (fig. 281). One of the bulbs is covered with muslin, and is kept continually moist by being connected with a reservoir of water by means of a string. Unless the air is saturated with moisture the wet bulb thermometer always indicates a lower temperature than the other, and the difference between the indications of the two thermometers is greater in proportion as the air can take up more moisture. The tension e of the aqueous vapour in the atmosphere may be calculated from the indications of the thermometer by means of the following empirical formula :—

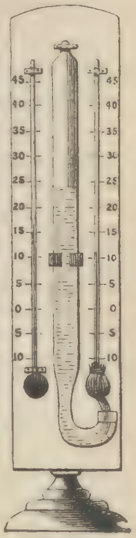


Fig. 281.

$$e = e' - 0{\cdot}00077\,(t - t')\,h,$$

in which e' is the maximum tension corresponding to the temperature of the wet bulb thermometer, h is the barometric height, and t and t' the respective temperatures of the dry and wet bulb thermometers. If, for example, $h = 750$ millimeters, $t = 15°$ C., $t' = 10°$ C.; according to the table of tensions (324), $e' = 9{\cdot}165$, and we have

$$e = 9{\cdot}165 - 0{\cdot}00077 \times 5 \times 750 = 6{\cdot}278.$$

This tension corresponds to a dew point of about 4·5° C. If the air had been saturated, the tension would have been 12·699, and the air is therefore about half saturated with moisture.

This formula expresses the result with tolerable accuracy, but the above constant 0·00077 requires to be controlled for different positions of the instrument; in small closed rooms it is 0·00128, in large rooms it is 0·00100, and in the open air without wind it is 0·00090: the number 0·00077 is its value in a large room with open windows. Regnault found that the difference in temperature of the two bulbs depends on the rapidity of the current of air; he also found that at a low temperature and in very moist air, the results obtained with the psychrometer differed from those yielded by his hygrometer. It is probable that the indications

of the psychrometer are only true for mean and high temperatures, and when the atmosphere is not too moist.

According to Glaisher the temperature of the dew point may be obtained by multiplying the difference between the temperatures of the wet and dry bulb by a constant depending on the temperature of the air at the time of observation, and subtracting the product thus obtained from this last-named temperature. The following are the numbers:—

Dry Bulb Temperature F.°	Factor	Dry Bulb Temperature F.°	Factor
Below 24°	8·5	34 to 35	2·8
24 to 25	6·9	35—40	2·5
25—26	6·5	40—45	2·2
26—27	6·1	45—50	2·1
27—28	5·6	50—55	2·0
28—29	5·1	55—60	1·9
29—30	4·6	60—65	1·8
30—31	4·1	65—70	1·8
31—32	3·7	70—75	1·7
32—33	3·3	75—80	1·7
33—34	3·0	80—85	1·6

These are often known as *Glaisher's factors.*

A formula frequently used in this country is that given by Dr. Apjohn. It is

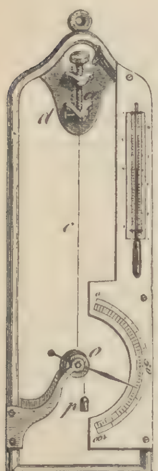


Fig. 282.

$$F = f - \frac{d}{88} \times \frac{h}{30}, \text{ or } F = f - \frac{d}{96} \times \frac{h}{30}$$

in which d is the difference of the wet and dry bulb thermometers in *Fahrenheit* degrees; h the barometric height in *inches*; f the tension of vapour for the temperature of the *wet bulb*, and F the elastic force of vapour at the dew point, from which the dew point may if necessary be found from the tables. The constant coefficient 88, for the specific heats of air and aqueous vapour, is to be used when the reading of the wet bulb is above 32° F. and 96 when it is below.

362. **Hygrometers of absorption.**—These hygrometers are based on the property which organic substances have, of elongating when moist, and of again contracting as they become dry. The most common form is the *hair* or *Saussure's hygrometer.*

It consists of a brass frame (fig. 282), on which is fixed a hair, c, fastened at its upper extremity in a clamp, a, provided with a screw, d. This clamp is moved by a screw b. The lower part of the hair passes round a pulley, o, and supports a small weight, p. On the pulley there is a needle, which moves along a graduated scale. When the hair becomes shorter the needle rises, when it becomes longer the weight p makes it sink.

The scale is graduated by calling that point zero at which the needle would stand if the air were completely dry, and 100 the point at which it stands in air completely saturated with moisture. The distance between these points is divided into 100 equal degrees.

Regnault has devoted much study in order to render the air hygrometer scientifically useful, but without success. And the utmost that can be claimed for it is that it can be used as a *hygroscope*; that is, an instrument which shows approximately whether the air is more or less moist, without giving any indication as to the quantity of moisture present. To this class belong the chimney ornaments, one of the most common forms of which is that of a small male and female figure, so arranged in reference to a little house, with two doors, that when it is moist the man goes out, and the woman goes in, and *vice versa* when it is fine. They are founded on the property which twisted strings or pieces of catgut possess, of untwisting when moist, and of twisting when dry.

As these hygroscopes only change slowly, their indications are always behindhand with the state of the weather; nor are they, moreover, very exact.

363. **Problem on hygrometry.**—To calculate the weight P of a volume of moist air V, the hygrometric state of which is E, the temperature t, and the pressure H, the density of the vapour being $\frac{5}{8}$ that of air.

From the second law of the mixture of gases and vapours, it will be seen that the moist air is nothing more than a mixture of V cubic inches of dry air at $t°$, under the pressure H minus that of the vapour, and of V cubic inches of vapour at $t°$ and the tension given by the hygrometric state; these two values, must, therefore, be found separately.

The formula $f = F \times E$ (355) gives the tension f of the vapour in the air, for E has been determined, and F is found from the tables. The tension f being known, if f' is the tension of the air, $f + f' = H$, from which $f' = H - f = H - FE$.

The question consequently resolves itself into calculating the weight of V cubic inches of dry air at $t°$, and the pressure H − FE, and then that of V cubic inches of vapour also at $t°$, but under the pressure FE.

Now V cubic inches of dry air under the given conditions weigh $\frac{0·31\ V\ (H - FE)}{(1 + \alpha t)\ 760}$, and we readily see from problem III. art. 348 that V cubic inches of vapour at $t°$, and the pressure FE, weigh $\frac{5}{8} \times \frac{0·31\ VFE}{(1 + \alpha t)\ 760}$. Adding these two weights, and reducing, we get

$$P = \frac{0·31\ V\ (H - \frac{3}{8}\ FE)}{(1 + \alpha t)\ 760}$$

If the air were saturated we should have $E = 1$, and the formula would thus be changed into that already found for the mixture of gases and saturated vapours (348).

This formula contains, besides the weight P, many variable quantities

V, E, H, and t, and, consequently, by taking successively each of these quantities as unknown, as many different problems might be proposed.

364. **Correction for the loss of weight experienced by bodies weighed in the air.**—It has been seen in speaking of the balance, that the weight which it indicates is only an apparent weight, and is less than the real weight. The latter may be deduced from the former when it is remembered that every body weighed in the air loses a weight equal to that of the displaced air (173). This problem is, however, very complicated, for not only does the weight of the displaced air vary with the temperature, the pressure, and the hygrometric state, but the volume of the body to be weighed, and that of the weights, vary also with the temperature; so that a double correction has to be made; one relative to the *weights*, the other to the body weighed.

Correction relative to the weights.—In order to make this correction let P be their weight in air, and Π their real weight in vacuo; further, let V be the volume of these weights at 0°, D the density of the substance of which they are made, and K its coefficient of linear expansion.

The volume V becomes $V(1+3Kt)$ at $t°$, hence this is the volume of air displaced by the *weights*. If μ be the weight of a cubic inch of air at t, and the pressure H at the time of weighing, we have

$$P=\Pi-\mu V(1+3Kt)$$

From the formula $P=VD$ (106) V may be replaced by $\frac{\Pi}{D}$, and the formula becomes

$$P=\Pi\left[1-\frac{\mu(1\times 3Kt}{D}\right] \quad . \quad . \quad . \quad . \quad (1)$$

which gives the value, in air, of a *weight* Π, when μ is replaced by its value. But since μ is the weight of a cubic inch of air more or less moist, at the temperature t and the pressure H, its value may be calculated by means of the formula in the foregoing paragraph.

Correction relative to the body weighed.—Let p be the apparent weight of the body to be weighed, π its real weight in vacuo, d its density, k its coefficient of expansion, and t its temperature, by the same reasoning as above we have

$$p=\pi\left[1-\frac{\mu(1+3kt}{d}\right] \quad . \quad . \quad . \quad . \quad (2)$$

By using the method of double weighing, and of a counterpoise whose apparent weight is p', the real ' weight π', the density d', and the coefficient k', and assuming that the pressure does not change, which is usually the case, we have again

$$p'=\pi'\left[1-\frac{\mu(1+3k't')}{d'}\right] \quad . \quad . \quad . \quad . \quad (3)$$

If a and b are the two arms of the beam, we have in the first weighing $ap=bp'$, and in the second $aP=bp$, whence $p=P$. Replacing P and p by their value deduced from the above quantities, we have

$$\pi \text{I} - \left[\frac{\mu(\text{I}+3kt)}{d}\right] = \Pi\left[\text{I} - \frac{\mu(\text{I}+3\text{K}t)}{\text{D}}\right]$$

whence

$$\pi = \Pi \frac{\text{I} - \frac{\mu(\text{I}+3\text{K}t)}{\text{D}}}{\text{I} - \frac{\mu(\text{I}+3kt)}{d}}$$

which solves the problem.

CHAPTER VII.

CONDUCTIVITY OF SOLIDS, LIQUIDS, AND GASES.

365. **Transmission of heat.**—When we stand at a little distance from a fire or other source of heat we experience the sensation of warmth. The heat is not transmitted by the intervening air; it passes through it without raising its temperature, for if we place a screen before the fire the sensation ceases to be felt. The heat from the sun reaches us in the same manner. The heat, which, as in this case, is transmitted to a body from the source of heat without affecting the temperature of the intervening medium, is said to be *radiated.*

Heat is transmitted in another way. When the end of a metal bar is heated, a certain increase of temperature is presently observed along the bar. Where the heat is transmitted in the mass of the body itself, as in this case, it is said to be *conducted.* We shall first consider the transmission of heat by conduction.

366. **Conductivity of solids.**—Bodies conduct heat with different degrees of facility. *Good conductors* are those which readily transmit heat such as are the metals; while *bad conductors,* to which class belong the resins, glass, wood, and more especially liquids and gases, offer a greater or less resistance to the transmission of heat.

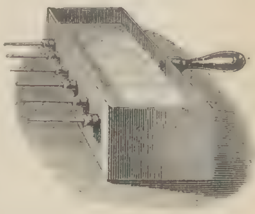


Fig. 283.

In order to compare roughly the conducting power or *conductivity* of different solids, Ingenhousz constructed the apparatus which bears his name, and which is represented in fig. 283. It is a metal trough, in which, by means of tubulures and corks, are fixed rods of the same dimensions, but of different materials; for instance, iron, copper, wood, glass. These rods extend to a slight distance in the trough, and the parts outside are coated with wax, which melts at 61°. The box being filled with boiling water, it is observed that the wax melts to a certain distance on the metallic rods, while on the others there is no trace of fusion. The conducting power is evidently greater in proportion as the wax has fused to a greater distance. The experiment is sometimes modified by attaching glass balls or marbles to

the ends of the rods by means of wax. As the wax melts, the balls drop off, and this in the order of their respective conductivities. The quickness with which melting takes place is however only a measure of the conducting power in case the metals have the same or nearly the same specific heat.

M. Despretz has compared the conducting powers of solids by means of the apparatus represented in fig. 284. It is a bar in which small cavities are made at intervals of 4 inches : these cavities contain mercury, and a delicate thermometer is placed in each of them. This bar is exposed at one end to a constant source of heat; the thermometers gradually rise until they indicate fixed temperatures, which are less according as the

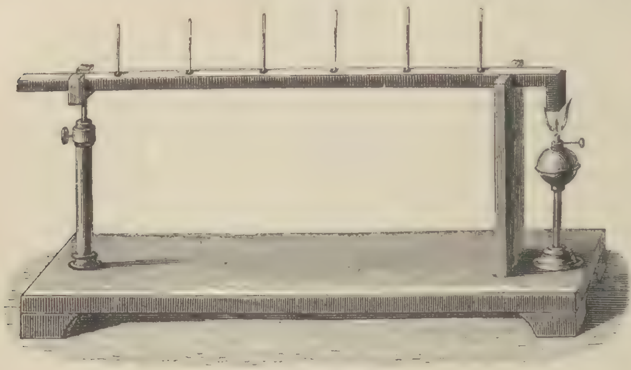


Fig. 284.

thermometers are further from the source of heat. By this method Despretz verified the following law : *If the distances from the source of heat increase in arithmetical progression, the excess of temperature over that of the surrounding air decreases in geometrical progression.*

This law, however, only prevails in the case of very good conductors, such as gold, platinum, silver, and copper; it is only approximately true for iron, zinc, lead, and tin, and does not apply at all to non-metallic bodies, such as marble, porcelain, etc.

Taking the conducting power of gold at 1000, Despretz has constructed the following table of conductivities :—

Platinum	981	Tin	304
Silver	973	Lead	179
Copper	897	Marble	23
Iron	374	Porcelain	12
Zinc	363	Brick earth	11

Wiedemann and Franz have made some valuable investigations on the conductivity of heat in metals. By making cavities in the bars, as in Despretz's method, their form is altered, and the continuity partially destroyed. Wiedemann and Franz have avoided this source of error by measuring the temperature of the bars in different places by applying to them the junction of a thermo-electric couple (373).

The metallic bars were made as regular as possible; one of the ends was heated to 100°, the rest of the bar being surrounded by air at a constant temperature. The thermo-electric couple was of small dimensions, in order not to extract too much heat.

By this method Wiedemann and Franz obtained results which differ considerably from those of Despretz. Representing the conductivity of silver by 100, they found for the other metals the following numbers:

Silver	100·0	Steel	11·6
Copper	73·6	Lead	8·5
Gold	53·2	Platinum	8·4
Tin	14·5	Rose's alloy	2·8
Iron	11·9	Bismuth	1·8

Organic substances conduct heat badly. De la Rive and De Candolle have shown that woods conduct better in the direction of their fibres than in a transverse direction; and have remarked upon the influence which this feeble conducting power, in a transverse direction, exerts in preserving a tree from sudden changes of temperature, enabling it to resist alike a sudden abstraction of heat from within, and the sudden accession of heat from without. Tyndall has also shown that this tendency is aided by the low conducting power of the bark, which is in all cases less than that of the wood.

Cotton, wool, straw, bran, etc., are all bad conductors.

367. **Senarmont's experiment.**—It is only in homogeneous bodies that heat is conducted with equal facility in all directions. If an aperture be made in a circular piece of ordinary glass covered with a thin layer of wax, and a platinum wire ignited by a voltaic current be held through the aperture, the wax will be melted round the hole in a circular form. Senarmont has made, on this principle, a series of experiments on the conductivity of heat in crystals. A plate cut from a crystal of the regular system was covered with wax, and a heated metallic point was held against it. The part melted had a circular form; but when plates of crystals belonging to other systems were investigated in a similar manner, it was found that the form of the line of equal temperature, that is, the limit of the melted part, varied with the different systems and with the position of the axes. In plates of uniaxial crystals cut parallel to the principal axis it was an ellipse, the major axis of which was in the direction of the principal axis. In plates cut perpendicular to the principal axis it was a circle. In biaxial crystals the line was always an ellipse.

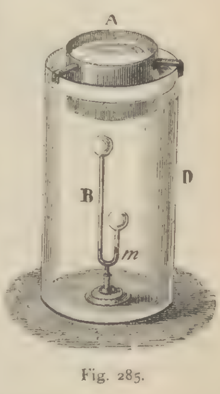


Fig. 285.

368. **Conductivity of liquids.**—The conductivity of liquids is very small, as is seen from the following experiment: A delicate thermoscope B, consisting of two glass bulbs, joined by a tube, m, in which there is a small index of coloured

liquid, is placed in a large cylindrical glass vessel, D (fig. 285). This vessel is filled with water at the ordinary temperature, and a tin vessel, A, containing oil at a temperature of two or three hundred degrees, is dipped in it. The bulb near the vessel A is only very slightly heated, and the index *m* moves through a very small distance. Other liquids give the same result. That liquids conduct very badly is also demonstrated by a simpler experiment. A long test tube is half filled with water and some ice so placed in it that it cannot rise to the surface. By inclining the tube and heating the surface of the liquid by means of a spirit lamp, the liquid at the top may be made to boil, while the ice at the bottom remains unmelted.

Despretz made a series of experiments with an apparatus analogous to that which has been described, but he maintained the liquid in the vessel, A, at a constant temperature, and arranged a series of thermometers one below the other in the vessel D. In this manner he found that the conductivity of heat in liquids obeys the same laws as in solids, but is much more feeble. For example, the conductivity of water is $\frac{1}{95}$ that of copper.

369. **Manner in which liquids are heated.**—When a column of liquid is heated at the bottom, ascending and descending currents are produced. It is by these that heat is mainly distributed through the liquid, and not by its conductivity. These currents arise from the expansion of the inferior layers, which, becoming less dense, rise in the liquid, and are replaced by colder and denser layers. They may be made visible by projecting bran or wooden shavings into water, which rise and descend with the currents. The experiment is arranged as shown in fig. 286. The mode in which heat is propagated in liquids and in gases is said to be by *convection.*

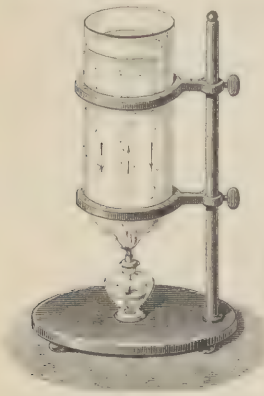


Fig. 286.

370. **Conductivity of gases.**—It is a disputed question whether gases have a true conductivity; but certainly when they are restrained in their motion their conductivity is very small. All substances, for instance, between whose particles air remains stationary, offer great resistance to the propagation of heat. This is well seen in straw, eider down, and furs. The propagation of heat in a gaseous mass is effected by means of the ascending and descending currents formed in it, as is the case with liquids.

The following experiment originally devised by Grove is considered to prove that gases have a certain conductivity. In a glass vessel provided with delivery tubes by which any gases can be introduced, or by which it can be exhausted, is a platinum wire which can be heated to redness by a voltaic battery. When the vessel is exhausted the platinum wire is gradually raised to a bright redness; on then allowing air to

enter the luminosity is greatly diminished, and if the vessel be exhausted and then hydrogen admitted, the luminosity quite disappears. This greater chilling of the wire in hydrogen than in air is considered by Magnus to be an effect of conduction ; while Tyndall ascribes it to the greater mobility of the particles of hydrogen.

371. **Applications.**—The greater or less conductivity of bodies meets with numerous applications. If a liquid is to be kept warm for a long time, it is placed in a vessel and packed round with non-conducting substances, such as shavings, straw, bruised charcoal. For this purpose water pipes and pumps are wrapped in straw at the approach of frost. The same means are used to hinder a body from becoming heated. Ice is transported in summer by packing it in bran, or folding it in flannel.

Double walls constructed of thick planks having between them any finely divided materials such as shavings, sawdust, dry leaves, etc., retain heat extremely well; and are likewise advantageous in hot countries, for they prevent its access. During the night the windows are opened, while during the day they are kept close. Pure silica in the state of rock crystal is a better conductor than lead, but in a state of powder it conducts very badly. If a layer of asbestos is placed on the hand a red-hot iron ball can be held without inconvenience. Red-hot cannon balls can be wheeled to the gun's mouth in wooden barrows partially filled with sand. Lava has been known to flow over a layer of ashes underneath which was a bed of ice, and the non-conducting power of the ashes has prevented the ice from fusion.

The clothes which we wear are not warm in themselves ; they only hinder the body from losing heat, in consequence of their spongy texture and the air they enclose. The warmth of bed covers and of counterpanes is explained in a similar manner. Double windows are frequently used in cold climates to keep a room warm—they do this by the non-conducting layer of air interposed between them. It is for the same reason that two shirts are warmer than one of the same material but of double the thickness. Hence too the warmth of furs, eider down, etc.

The small conducting power of felt is used in the North of Europe in the construction of the *Norwegian stove.*

It consists merely of a wooden box with a thick lining of felt on the inside. In the centre is a cavity in which can be placed a stew-pan provided with a cover. On the top of this is a lid, also made of felt, so that the pan is surrounded by a very badly conducting envelope. Meat, with water and suitable additions, are placed in the pan, and the contents are then raised to boiling. The whole is then enclosed in the box and left to itself; the cooking will go on without fire, and after the lapse of several hours it will be quite finished. The cooling down is very slow owing to the bad conducting power of the lining; at the end of three hours the temperature is usually not found to have sunk more than from 10° to 15°.

That water boils more rapidly in a metallic vessel than in one of porcelain of the same thickness; that a burning piece of wood can be held

close to the burning part with the naked hand, while a piece of iron heated at one end can only be held at a great distance, are easily explained by reference to their various conductivities.

The sensation of heat or cold which we feel when in contact with certain bodies is materially influenced by their conductivity. If their temperature is lower than ours, they appear colder than they really are, because from their conductivity heat passes away from us. If, on the contrary, their temperature is higher than that of our body, they appear warmer from the heat which they give up at different parts of their mass. Hence it is clear why carpets, for example, are warmer than wooden floors, and why the latter are warmer than stone floors.

CHAPTER VIII.

RADIATION OF HEAT.

372. **Radiant heat.** It has been already stated (365) that heat could be transmitted from one body to another without altering the temperature of the intervening medium. If we stand in front of a fire we experience a sensation of warmth which is not due to the temperature of the air, for if a screen be interposed the sensation immediately disappears, which would not be the case if the surrounding air had a high temperature. Hence bodies can send out rays which excite heat, and which penetrate through the air without heating it, as rays of light through transparent bodies. Heat thus propagated is said to be *radiated*; and we shall use the terms *ray of heat*, or *thermal* or *calorific ray*, in a similar sense to that in which we use the term *ray of light* or *luminous ray*.

We shall find that the property of radiating heat is not confined to luminous bodies, such as a fire or a red-hot ball, but that bodies of all temperatures radiate heat. It will be convenient to make a distinction between *luminous* and *obscure* rays of heat.

373. **Detection and measurement of radiant heat.**—In demonstrating the phenomena of radiant heat, very delicate thermometers are required, and the thermo-electrical multiplier of Melloni is used for this purpose with great advantage; for it not only indicates minute differences of temperature, but it also measures them with accuracy.

This instrument cannot be properly understood without a knowledge of the principles of thermo-electricity, for which Book X must be consulted. It may, however, be stated here, that when two different metals are soldered together at one end (fig. 287), the free ends being joined by a wire, when the soldering is heated, a current of electricity circulates through the system; if, on the contrary, the soldering be cooled, a current is also produced, but it circulates in exactly the opposite directions. If a number of such pairs be alternately soldered together, as represented

in fig. 288, the intensity of the current produced by heating the ends is increased; or, what amounts to the same thing, a smaller degree of heat will produce the same effect. Such an arrangement of a number of thermo-electric pairs is called a *thermo-electric battery* or *pile*.

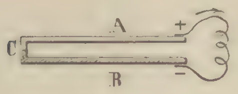


Fig. 287.

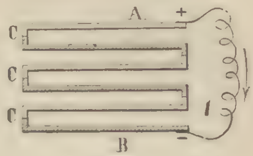


Fig. 288.

Melloni's thermo-multiplier consists of a thermo-electric pile connected with a delicate galvanometer. The thermo-electric pile is constructed of a number of minute bars of bismuth and antimony soldered together alternately, though kept insulated from each other, and contained in a

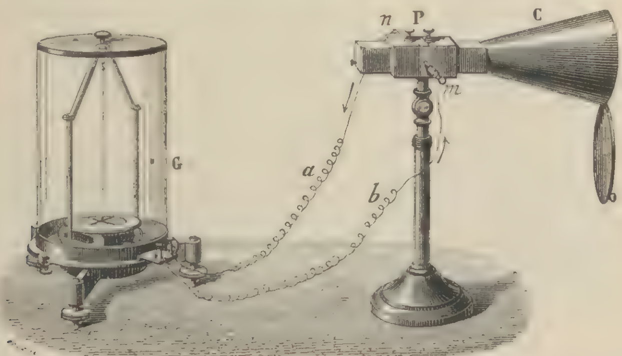


Fig. 289.

rectangular box P, fig. 289. The terminal bars are connected with two binding screws *m* and *n*, which in turn are connected with the galvanometer G by means of the wires *a* and *b*.

The galvanometer consists of a quantity of fine insulated copper wire coiled round a frame, in the centre of which a delicate magnetic needle is suspended by means of a silk thread. When an electric current is passed through this coil, the needle is deflected by an angle which depends on the intensity of the current. This angle is measured on a dial by an index connected with the needle.

It may then be sufficient to state that the thermo-electric pile being connected with the galvanometer by means of the wires *a* and *b*, an excess of temperature at one end of the pile causes the needle to be deflected through an angle which depends on the extent of this excess; and

similarly if the temperature be depressed below that of the other end, a corresponding deflection is produced in the opposite direction.

The object of the conical part C is to concentrate the thermal rays on the face of the pile.

374. **Laws of radiation.** The radiation of heat is governed by three laws :

I. *Radiation takes place in all directions round a body.* If a thermometer be placed in different positions round a heated body, it indicates everywhere a rise in temperature.

II. *In a homogeneous medium, radiation takes place in a right line.* For, if a screen be placed in a right line which joins the source of heat and the thermometer, the latter is not affected.

But in passing obliquely from one medium into another, as from air into a glass, calorific like luminous rays become deviated, an effect known as *refraction.* The laws of this phenomenon are the same for heat as for light, and they will be more fully discussed under the latter subject.

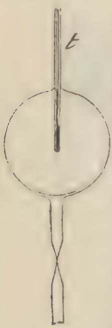


Fig. 290.

III. *Radiant heat is propagated in vacuo as well as in air.* This is demonstrated by the following experiments:

In the bottom of a glass flask a thermometer is fixed in such a manner that its bulb occupies the centre of the flask (fig. 290). The neck of the flask is carefully narrowed by means of the blowpipe, and then the apparatus having been suitably attached to an air pump, a vacuum is produced in the interior. This having been done, the tube is sealed at the narrow part. On immersing this apparatus in hot water, or on bringing near it some hot charcoal, the thermometer is at once seen to rise. This could only arise from radiation through the vacuum in the interior, for glass is so bad a conductor, that the heat could not travel with this rapidity through the sides of the flask and the stem of the thermometer.

375. **Causes which modify the intensity of radiant heat.**—By the *intensity of radiant heat* is understood the quantity of heat received on the unit of surface. Three causes are found to modify this intensity ; the temperature of the source of heat, its distance, and the obliquity of the caloric rays in reference to the surface which emits them. The laws which regulate these modifications may be thus stated:

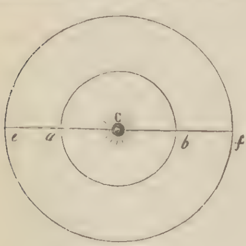


Fig. 291.

I. ***The intensity of radiant heat is proportional to the temperature of the source.***

II. ***The intensity is inversely as the square of the distance.***

III. *The intensity is less, the greater the obliquity of the rays with respect to the radiating surface.*

The first law is demonstrated by placing a metallic box containing water at 10°, 20°, or 30°, successively at equal distances from the bulb of

a differential thermometer. The temperatures indicated by the latter are then found to be in the same ratio as those of the box: for instance, if the temperature of that corresponding to the box at 10° be 2°, those of others will be 4° and 6° respectively.

The truth of the second law follows from the geometrical principle that the surface of a sphere increases as the square of its radius. Suppose a hollow sphere, *ab* (fig. 291), of any given radius, and a source of heat, C, in its centre; each unit of surface in the interior receives a certain quantity of heat. Now, a sphere, *ef*, of double the radius will present a surface four times as great: its internal surface contains, therefore, four times as many units of surface, and as the quantity of heat emitted is the same, each unit must receive one-fourth the quantity.

To demonstrate the same law experimentally, a narrow tin plate box is taken (fig. 292), filled with hot water, and coated on one side with

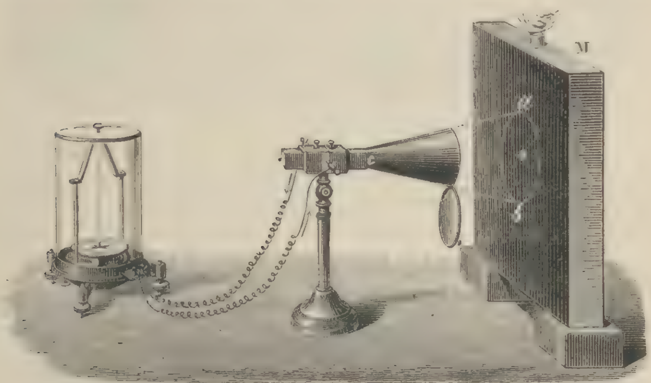


Fig. 292.

lampblack. The thermo-battery with its conical reflector is placed so that its face is at a certain definite distance *co*, say 9 inches, from this box, and the cover having been lowered, the needle of the galvanometer is observed to be deflected through 80°, for example.

If now the battery is removed to a distance, CO, double that of *co*, the deflection of the galvanometer remains the same, which shows that the battery receives the same amount of heat; the same is the case if the battery is removed to three or four times the distance. This result, though apparently in opposition to the second law, really confirms it. For at first the battery only receives heat from the circular portion *ab* of the side of the box, while, in the second case, the circular portion AB radiates towards it. But, as the two cones ACB and *acb* are similar, and the height of ACB is double that of *acb*, the diameter AB is double that of *ab*, and therefore the area AB is four times as great as that of *ab*, for the areas of circles are proportional to the squares of the radii. But since

the radiating surface increases as the square of the distance, while the galvanometer is stationary, the heat received by the battery must be inversely as this same square.

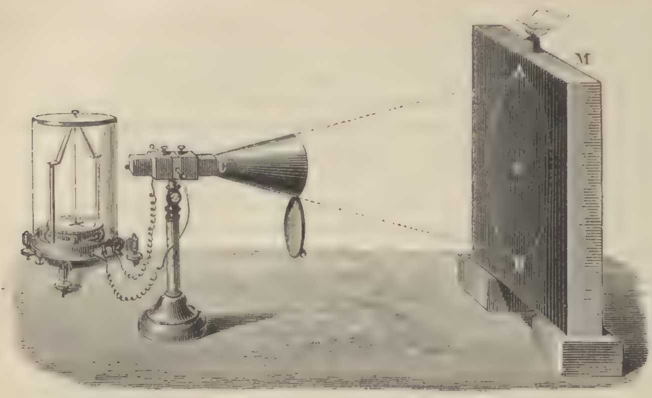


Fig. 293.

The third law is demonstrated by means of the following experiment, which is a modification of one originally devised by Leslie (fig. 294). P represents the thermo-multiplier which is connected with its galvanometer, and A, a metal cube full of hot water. The cube being first

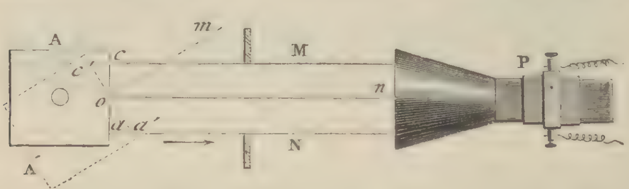


Fig. 294.

placed in such a position A that its front face *ac* is vertical, the deflection of the galvanometer is noted. Supposing it amounts to 45°, this represents the radiation from *ac*. If this now be turned in the direction represented by A′, the galvanometer is still found to mark 45°.

The second surface is larger than the first, and it therefore sends more rays to the mirror. But as the action on the thermometer is no greater than in the first case, it follows that in the second case, where the rays are oblique, the intensity is less than in the first case, where they are perpendicular.

In order to express this in a formula, let i be the intensity of the rays emitted perpendicularly to the surface, and i' that of the oblique rays. These intensities are necessarily inversely as the surfaces *ac* and *a′c′*, for

the effect is the same in both cases, and therefore $i' \times$ surface $a'c' = i \times$ surface ac; hence $i' = i \frac{\text{surf. } ac}{\text{surf. } a'c'} = i \frac{ac}{a'c'} = i \cos aoa'$; which signifies that *the intensity of oblique rays is proportional to the cosine of the angle which these rays form with the normal to the surface*; for this angle is equal to the angle aoa'. This law is known as the *law of the cosine*; it is, however, not general; MM. Desains and De la Provostaye have shown that it is only true within very narrow limits, that is, only with bodies which, like lampblack, are entirely destitute of reflecting power (384).

376. **Mobile equilibrium. Theory of exchanges.**—Prevost of Geneva suggested the following hypothesis in reference to radiant heat, known as Prevost's *theory of exchanges*, which is now universally admitted. All bodies, whatever their temperature, constantly radiate heat in all directions. If we imagine two bodies at different temperatures placed near one another, the one at a higher temperature will experience a loss of heat, its temperature will sink because the rays it emits are of greater intensity than those it receives; the colder body, on the contrary, will rise in temperature because it receives rays of greater intensity than those which it emits. Ultimately the temperature of both bodies becomes the same, but heat is still exchanged between them, only each receives as much as it emits, and the temperature remains constant. This state is called the *mobile equilibrium of temperature.*

377. **Newton's law of cooling.**—A body placed in a vacuum is only cooled or heated by radiation. In the atmosphere it becomes cooled or heated by its contact with the air according as the latter is colder or hotter than the radiating body. In both cases the velocity of cooling or of heating—that is, *the quantity of heat lost or gained in a second*—is greater according as the difference of temperature is greater.

Newton has enunciated the following law in reference to the cooling or heating of a body: *The quantity of heat lost or gained by a body in a second is proportional to the difference between its temperature and that of the surrounding medium.* Dulong and Petit have proved that this law is not so general as Newton supposed, and only applies where the differences of temperature do not exceed 15° to 20°. Beyond that, the quantity of heat lost or gained is greater than that required by this law.

Two consequences follow from Newton's law:

i. When a body is exposed to a constant source of heat, its temperature does not increase indefinitely, for the quantity which it receives in the same time is always the same; while that which it loses increases with the excess of the temperature over that of the surrounding medium. Consequently a point is reached, at which the quantity of heat emitted is equal to that absorbed, and the temperature then remains stationary.

ii. Newton's law, as applied to the differential thermometer, shows that its indications are proportional to the quantities of heat which it receives. If one of the bulbs of a differential thermometer receives rays of heat from a constant source, the instrument exhibits first increasing temperatures, but afterwards becomes stationary. In this case, the quantity of heat which it receives is equal to that which it emits. But the latter is

proportional to the excess of the temperature of the bulb above that of the surrounding atmosphere, that is, to the number of degrees indicated by the thermometer; consequently, the temperature indicated by the differential thermometer is proportional to the quantity of heat it receives.

REFLECTION OF HEAT.

378. **Laws of reflection.**—When thermal rays fall upon a body they are, speaking generally, divided into two parts, one of which penetrates the body, while the other rebounds as if repelled from the surface like an elastic ball. This is said to be *reflected*.

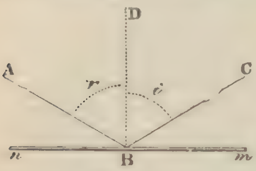


Fig. 295.

If *mn* be a plane reflecting surface (fig. 295), CB an *incident ray*, BD a line perpendicular to the surface called the *normal*, and BA the *reflected ray*; the angle CBD is called the *angle of incidence*, and DBA the *angle of reflection*. The reflection of heat, like that of light, is governed by the two following laws:

I. *The angle of reflection is equal to the angle of incidence.*

II. *Both the incident and the reflected ray are in the same plane with the normal to the reflecting surface.*

379. **Experimental demonstration of the laws of reflection of heat.**—This may be effected by means of Melloni's thermo-pile and also by the conjugate mirrors (381). Figure 296 represents the arrangement

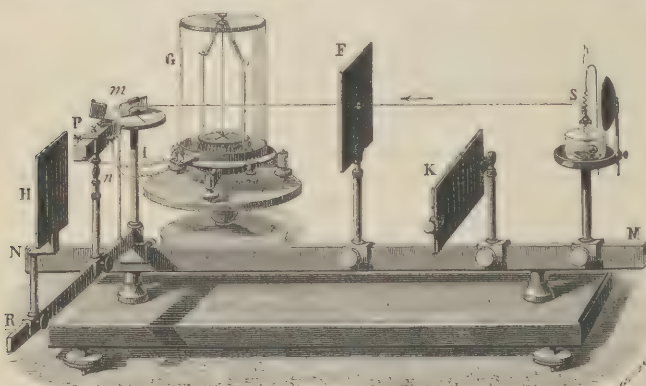


Fig. 296.

adopted in the former case. MN is a horizontal bar, about a metre in length, graduated in millimeters, on which slide various parts, which can be clamped by means of screws. The source of heat, S, is a platinum spiral, kept at a white heat in a spirit lamp. A screen, K, when raised,

cuts off the radiation from the source; a second screen F, with an aperture in the centre, gives the rays a parallel direction. At the other end is an upright rod, I, with a graduated dial, the zero of which is in the direction of MN, and therefore parallel to the pencil S*m*. In the centre of the dial is an aperture, in which turns an axis which supports a metallic mirror *m*. About this axis turns an index, R, on which is fixed the thermo-battery, P, in connection with the galvanometer, G. H is a screen, the object of which is to cut off any direct radiation from the source of heat towards the battery. In order not to mask the battery it is not represented in the position it occupies in the experiment.

By lowering the screen K, a pencil of parallel rays, passing through the aperture F, falls upon the mirror *m*, and is there reflected. If the index R is not in the direction of the reflected pencil, this latter does not impinge on the pile, and the needles of the galvanometer remain stationary; but by slowly turning the index R, a position is found at which the galvanometer attains its greatest deviation, which is the case when the battery receives the reflected pencil perpendicularly to its surface. Reading off then on the dial the position of a small needle perpendicular to the mirror, it is observed that this bisects the angle formed by the incident and the reflected pencil, which demonstrates the first law.

The second law is also proved by the same experiment, for the various pieces of the apparatus are arranged so that the incident and reflected ray are in the same horizontal plane, and therefore at right angles to the reflecting surface, which is vertical.

380. **Reflection from concave mirrors.** — *Concave mirrors* or *reflectors*, are polished spherical or parabolic surfaces of metal or of glass, which are used to concentrate luminous or calorific rays in the same point.

We shall only consider the case of spherical mirrros. Fig. 298 represents two of these mirrors; fig. 297 gives a medial section, which is called the *principal section*. The centre C of the sphere to which the

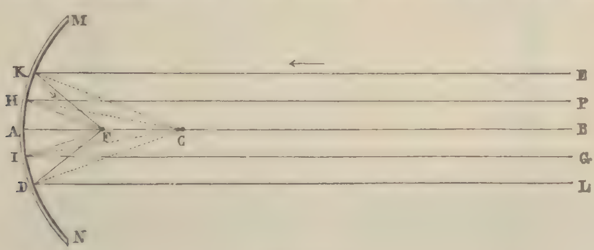


Fig. 297.

mirror belongs is called the *centre of curvature*; the point A, the middle of the reflector, is the *centre of the figure*; the straight line AB passing through these points, is the *principal axis* of the mirror.

In order to apply to spherical mirrors the laws of reflection from plane surfaces, they are considered to be composed of an infinite number of in-

finitely small plane surfaces, each belonging to the corresponding tangent plane, the normals to these small surfaces are all radii of the same sphere, and therefore meet at its centre, the centre of curvature of the mirror.

Suppose now, on the axis AB of the mirror MM, a source of heat so distant that the rays EK, PH . . . . . which emanate from it may be considered as a parallel. From the hypothesis that the mirror is composed of an infinitude of small planes, the ray EK is reflected from the plane K just as from a plane mirror; that is to say, CK being the normal to this plane, the reflected ray takes a direction such that the angle CKF is equal to the angle CKE. The other rays, PH, GI . . . . . are reflected in the same manner, and all converge approximately towards the same point F, on the line AC. There is then a concentration of the rays in this point, and consequently a higher temperature than at any other point. This point is called the *focus*, and the distance from the focus to the mirror at A is the *focal distance*.

In the above figure the heat is propagated along the lines EKF, LDF, in the direction of the arrows; but, conversely, if the heated body be placed at F, the heat is propagated along the lines FKE, FDL, so that the rays emitted from the focus are nearly parallel after reflection.

381. **Verification of the laws of reflection.**—The following experiment, which was made for the first time, by Pictet and Saussure, and which is known as the *experiment of the conjugate mirrors*, demonstrates not only the existence of the foci, but also the laws of reflection. Two

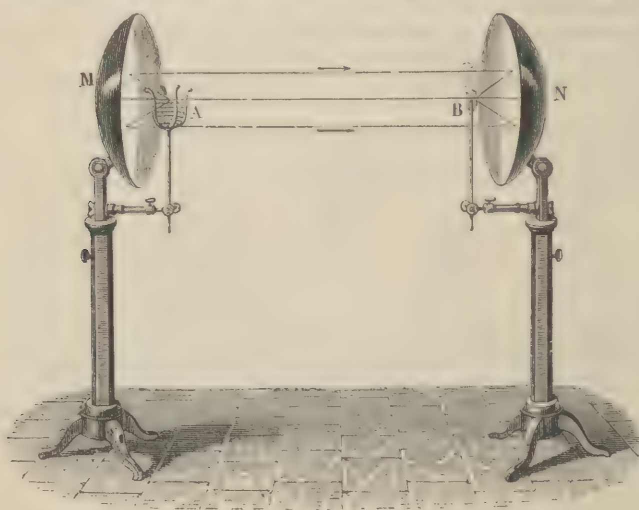


Fig. 298.

reflectors, M and N (fig. 298), are arranged at a distance of 4 to 5 yards, and so that their axes coincide. In the focus of one of them, A, is placed a small wire basket containing a red-hot iron ball. In the focus of the

other is placed B, an inflammable body, such as gun-cotton or phosphorus. The rays emitted from the focus A are first reflected from the mirror M, in a direction parallel to the axis (380), and impinging on the other mirror, N, are reflected so that they coincide in the focus B. That this is so, is proved by the fact that the gun-cotton in this point takes fire, which is not the case if it is above or below it.

The experiment also serves to show that light and heat are reflected in the same manner. For this purpose a lighted candle is placed in the focus of A, and a ground glass screen in the focus of B, when a luminous focus is seen on it exactly in the spot where the gun-cotton ignites. Hence the luminous and the calorific foci are produced at the same point, and the reflection takes place in both cases according to the same laws, for it will be afterwards shown that for light the angle of reflection is equal to the angle of incidence, and that both the incident and the reflected rays are in the same plane perpendicular to the plane reflecting surface.

In consequence of the high temperature produced in the foci of concave mirrors they have been called *burning mirrors*. It is stated that Archimedes burnt the Roman vessels before Syracuse by means of such mirrors. Buffon constructed burning mirrors of such power as to prove that the feat attributed to Archimedes was possible. The mirrors were made of a number of silvered plane mirrors about 8 inches long by 5 broad. They could be turned independently of each other in such a manner that the rays reflected from each coincided in the same point. With 128 mirrors and a hot summer's sun Buffon ignited a plank of tarred wood at a distance of 70 yards.

382. **Reflection in a vacuum.**—Heat is reflected in a vacuum as well as in air, as is seen from the following experiment (fig. 299), due to Sir Humphry Davy. Two small concave reflectors were placed opposite each other under the receiver of an air pump. In the focus of one was placed a delicate thermometer, and in the focus of the other a platinum wire made incandescent by means of a galvanic current. The thermometer was immediately seen to rise several degrees, which could only be due to reflected heat, for the thermometer did not show any increase of temperature if it were not exactly in the focus of the second reflector.

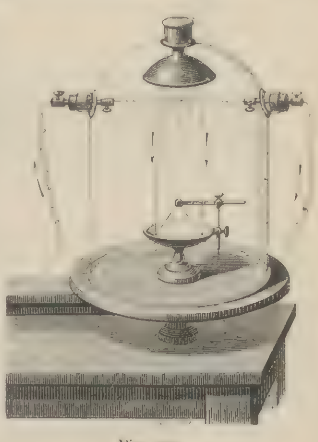


Fig. 299.

383. **Apparent reflection of cold.**—If two mirrors are arranged as represented in fig. 299, and a piece of ice is placed in one of the foci instead of the red-hot ball, the surrounding temperature being greater than zero, a differential thermometer placed in

the focus of the second reflector would exhibit a decrease in temperature of several degrees. This appears at first to be caused by the emission of *frigorific* rays from ice. It is, however, easily explained from what has been said about the mobile equilibrium of temperature (376). There is still an exchange of temperature, but here the thermometer is the warmest body. As the rays which the thermometer emits are more intense than those emitted by the ice, the former gives out more heat than it receives, and hence its temperature sinks.

The sensation of cold experienced when we stand near a plaster or a stone wall whose temperature is lower than that of our body, or when we stand in front of a wall of ice, is explained in the same way.

384. **Reflecting power.**—The *reflecting power* of a substance is its property of throwing off a greater or less proportion of incident heat.

This power varies in different substances. In order to study this power in different bodies without having recourse to as many reflectors, Leslie arranged his experiments as shown in fig. 300. The source of

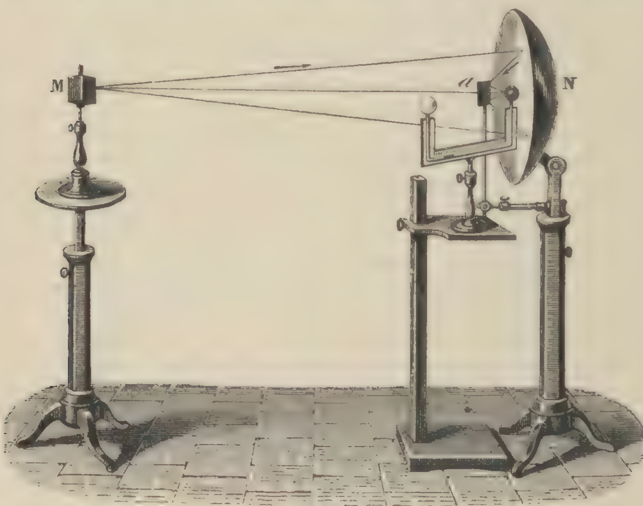


Fig. 300.

heat is a cubical canister, M, now known as *Leslie's cube*, filled with hot water. A plate, *a*, of the substance to be experimented upon is placed on the axis of a reflecting mirror between the focus and the mirror. In this manner the rays emitted by the source are first reflected from the mirror and impinge on the plate *a*, where they are again reflected and converge to a focus between the plate and the mirror, in which point a differential thermometer is placed. The reflector and the thermometer are always in the same position, and the water of the cube is always kept at 100°, but it is found that the temperature indicated by the thermometer varies with the nature of the plate. This method gives a means of

determining, not the absolute reflecting power of a body, but its power relatively to that of some body taken as a standard of comparison. For, from what has been said on the application of Newton's law to the differential thermometer, the temperatures which this instrument indicates are proportional to the quantities of heat which it receives. Hence, if in the above experiment, a plate of glass causes the temperature to rise 1°, and a plate of lead 6°, it follows that the quantity of heat reflected by the latter is six times as great as that reflected by the former. For the heat emitted by the source remains the same, the concave reflector receives the same portion, and the difference can only arise from the reflecting power of the plates *a*.

By this method Leslie determined the reflecting powers of the following substances, relatively to that of brass, taken as 100 :

Polished brass	100	Indian ink	13
Silver	90	Amalgamated tin	10
Polished tin	80	Glass	10
Steel	70	Oiled glass	5
Lead	60	Lampblack	0

The numbers only represent the relative reflecting power as compared with that of brass. Their *absolute power* is the *relation of the quantity of heat reflected to the quantity of heat received.* Melloni first determined the absolute reflecting power of a certain number of bodies. Desains and De la Provostaye, who also examined it for certain metals, obtained the following results by means of Melloni's thermo-multiplier (373), the heat being reflected at an angle of 50° :

Silver plate	0·97	Steel	0·82
Gold	0·95	Zinc	0·81
Brass	0·93	Iron	0·77
Platinum	0·83	Cast iron	0·74

We shall presently see (388) what are the causes which modify the reflecting power.

385. **Absorbing power.**—The *absorbing power* of a body is its property of allowing a greater or less quantity of incident heat to pass into its mass. Its absolute value is the ratio of the quantity of heat absorbed to the quantity of heat received.

The absorbing power of a body is always inversely as its reflecting power : a body which is a good absorbent is a bad reflector, and *vice versa.* It was formerly supposed that the two powers were exactly complementary, that the sum of the reflected and absorbed heat was equal to the total quantity of incident heat. This is not the case ; it is always less : the incident heat is divided into three parts—1st, one which is absorbed ; 2nd, another which is reflected regularly—that is, according to laws previously demonstrated (378) ; and a third, which is irregularly reflected in all directions, and which is called *scattered* or *diffused heat.*

In order to determine the absorbing power of bodies, Leslie used the apparatus which he employed in determining the reflecting powers (384).

But he suppressed the plate *a*, and placed the bulb of the thermometer in the focus of the reflector. This bulb being then covered successively with lampblack, or varnish, or with gold, silver, or copper foil, etc., the thermometer exhibited a higher temperature under the influence of the source of heat, M, according as the substance with which the bulb was covered absorbed more heat. Leslie found in this way that the absorbing power of a body is greater the less its reflecting power. In these experiments, however, the relation of the absorbing powers cannot be deduced from that of the temperatures indicated by the thermometer, for Newton's law is not exactly applicable in this case, as it only prevails for bodies whose substance does not vary, and here the covering of the bulb varied with each observation. But we shall presently show (387) how the comparative absorbing powers may be deduced from the ratios of the emissive powers.

Taking as a source of heat a canister filled with water at 100°, Melloni found by means of the thermo-multiplier the following relative absorbing powers :

Lampblack	100	Indian ink	85
White lead	100	Shellac	72
Isinglass	91	Metals	13

386. **Radiating power.**—The *radiating* or *emissive power* of a body is its capability of emitting at the same temperature and with the same extent of surface greater or less quantities of heat.

The apparatus represented in fig. 300 was also used by Leslie in determining the radiating power of bodies. For this purpose the bulb of the thermometer was placed in the focus of the reflector, and the faces of the canister M were formed of different metals, or covered with different substances, such as lampblack, paper, etc. The cube being filled with hot water, at 100°, and all other conditions remaining the same, Leslie turned each face of the cube successively towards the reflectors, and noted the temperature each time. That face which was coated with lampblack caused the greatest elevation of temperature, and the metal faces the least. Applying Newton's law, and representing the heat emitted by lampblack as 100, Leslie formed the following table of radiating powers :

Lampblack	100	Isinglass	80
White lead	100	Tarnished lead	45
Paper	98	Mercury	20
Sealing wax	95	Polished lead	19
Ordinary white glass	90	Polished iron	15
Indian ink	88	Tin, gold, silver, copper, etc.	12

It will be seen that, in this table, the order of the bodies is exactly the reverse of that in the tables of reflecting powers.

The radiating powers of several substances were determined by Melloni by the same method as that of Leslie, but using the thermo-multiplier instead of the differential thermometer. This has also since

been done more exactly by Desains and De la Provostaye, who used the same instrument, but avoided certain sources of error incidental to previous methods. They found in this manner the following numbers compared with lampblack as 100:

Platinum foil	10·80	Pure silver laminated	3·00
Burnished platinum	9·50	„ burnished	2·50
Silver deposited chemically	5·36	„ deposited chemically and burnished	2·25
Copper foil	4·90		
Gold leaf	4·28		

It appears, therefore, that the radiating power found by Leslie for the metals is too large.

387. **Identity of the absorbing and radiating powers.**—The absorbing power of a body cannot be accurately deduced from its reflecting power, because the two are not exactly complementary. But the absorbing power would be determined if it could be shown that in the same body it is equal to the radiating power. This conclusion has been drawn by Dulong and Petit from the following experiments:—In a large glass globe, blackened on the inside, was placed a thermometer at a certain temperature, 15° for example; the globe was kept at zero by surrounding it with ice, and having been exhausted by means of a tubulure connected with the air pump, the time was noted which elapsed while the thermometer fell through 5°. The experiment was then made in the contrary direction; that is, the sides of the globe were heated to 15°, while the thermometer was cooled to zero: the time was then observed which the thermometer occupied in rising through 5°. It was found that this time was exactly the same as that which the thermometer had taken in sinking through 5°, and it was thence concluded that the radiating power is equal to the absorbing power for the same body, and for the same difference between its temperature and the temperature of the surrounding medium, because the quantities of heat emitted or absorbed in the same time are equal.

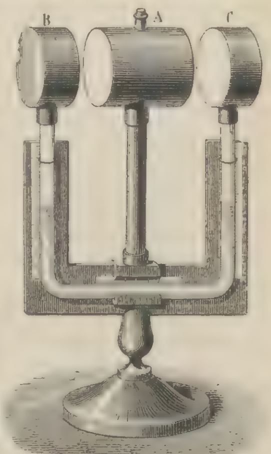


Fig. 301.

This point may also be demonstrated by means of the following apparatus devised by Ritchie. Fig. 301 represents what is virtually a differential thermometer, the two glass bulbs of which are replaced by two cylindrical reservoirs B and C, of metal, and full of air. Between them is a third and larger one A, which can be filled with hot water by means of a tubulure. The faces of B and of A, which face the right, are coated with lampblack; those of C and A, which face the left, are either painted white, or are coated with silver foil. Thus of the two faces opposite each other, one is black and the other white; hence when

the cylinder A is filled with hot water, its white face radiates towards the black face of B, and its black face towards the white face of C. Under these circumstances the liquid in the stem does not move, indicating that the two reservoirs are at the same temperature. On the one hand, the greater emissive power of the black face of A is compensated by the smaller absorptive power of the white face of C; while, on the other hand, the feebler radiating power of the white face of A is compensated by the greater absorbing power of the black face of B.

The experiment may be varied by replacing the two white faces by discs of paper, glass, porcelain, &c.

388. **Causes which modify the reflecting, absorbing, and radiating powers.**—As the radiating and absorbing powers are equal, any cause which affects the one affects the other also. And as the reflecting power varies in an inverse manner, whatever increases it diminishes the radiating and absorbing powers, and *vice versa.*

It has been already stated that these different powers vary with different bodies, and that metals have the greatest reflecting power, and lampblack the feeblest. In the same body these powers are modified by the degree of polish, the density, the thickness of the radiating substance, the obliquity of the incident or emitted rays, and, lastly, by the nature of the source of heat.

It has been assumed usually that the reflecting power increases with the polish of the surface, and that the other powers diminish therewith. But Melloni showed that by scratching a polished metallic surface its reflecting power was sometimes diminished and sometimes increased. This phenomenon he attributed to the greater or less density of the reflecting surface. If the plate had been originally hammered, its homogeneity would be destroyed by this process, the molecules would be closer together on the surface than in the interior, and the reflecting power would be increased. But if the surface is scratched the internal and less dense mass becomes exposed, and the reflecting power diminished. On the contrary, in a plate which has not been hammered and which is homogeneous, the reflecting power is increased when the plate is scratched, because the density at the surface is increased by the scratches.

The experiments of Leslie, Rumford, and Melloni further prove, that the thickness of the radiating substance also modifies its emissive power. The latter philosopher found that when the faces of a cube filled with water at a constant temperature were varnished, the emissive power increased with the number of layers up to 16 layers, and that above that point it remained constant, whatever the number. He calculated that the thickness of the 16 layers was 0·04 of a millimeter. With reference to metals, gold leaves of 0·008, 0·004, and 0·002 of a millimeter in thickness, having been successively applied on the sides of a cube of glass, the diminution of radiant heat was the same in each case. It appears therefore that, between certain limits, the thickness of the radiating layer of metal is without influence.

The absorbing power varies with the inclination of the incident rays. It is greatest at the normal incidence, that is, at right angles; and it di-

minishes in proportion as the incident rays deviate from the normal. This is one of the reasons why the sun is hotter in summer than in winter, because, in the former case, the solar rays are less oblique.

The radiating power of gaseous bodies in a state of combustion is very weak, as is seen by bringing the bulb of a thermometer near a hydrogen flame, the temperature of which is very high. But if a platinum spiral be placed in this flame, it assumes the temperature of the flame, and radiates a considerable quantity of heat, as is indicated by the thermometer. It is for an analogous reason that the flames of oil and of gas lamps radiate more than a hydrogen flame, in consequence of the excess of carbon which they contain, and which, not being entirely burned, becomes incandescent in the flame.

389. **Melloni's researches on radiant heat.**—For our knowledge of the phenomena of the reflection, emission, and absorption of heat which have up to now been described, science is indebted mainly to Leslie. But since his time the discovery of other and far more delicate modes of detecting and measuring heat has not only extended and corrected our previous knowledge, but has led to the discovery of other phenomena of radiant heat, which without such improved means must have remained unknown.

This advanee in science is due to an Italian philosopher, Melloni, who first applied the thermo-electric pile, invented by Nobili, to the measurement of very small differences of temperature; a method of which a preliminary account has already been given.

In his experiments Melloni used five sources of heat—1st, a Locatelli's lamp—one, that is, without a glass chimney, but provided with a reflector (fig. 302); 2nd, an Argand lamp, that is, one with a chimney and a double draught; 3rd, a platinum spiral, kept red hot by a spirit lamp (fig. 303);

Fig. 302.

Fig. 303.

Fig. 304.

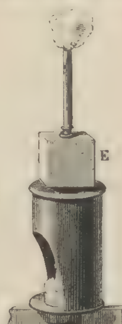


Fig. 305.

4th, a blackened copper plate, kept at a temperature of about 400 degrees by a spirit lamp (fig. 304); 5th, a copper cube, blackened on the outside and filled with water at 100° (fig. 305).

390. **Dynamical theory of heat.**—Before describing the results arrived at by Melloni and others it will be convenient to state here the view now generally taken of the nature of heat and of the mode in which it is

propagated. For additional information the chapter on the Mechanical Theory of Heat and the book on Light should be read. According to what is called the *mechanical or dynamical theory of heat*, a hot body is nothing more than one whose particles are in a state of vibration. The higher the temperature of the body the more rapid are these vibrations, and a diminution in temperature is but a diminished rapidity of vibration of the particles. The propagation of heat through a bar is due to a gradual communication of this vibratory motion from the heated part to the rest of the bar. A good conductor is one which readily takes up and transmits the vibratory motion from particle to particle, while a bad conductor is one which takes up and transmits the motion with difficulty. But even through a good conductor the propagation of this motion is comparatively slow; how then are we to explain the instantaneous perception of heat experienced when a screen is removed from a fire, or when a cloud is drifted from the face of the sun? In this case, the heat passes from one body to another without affecting the temperature of the medium which transmits it. In order to explain these phenomena it is imagined that all space, the interplanetary spaces as well as the interstices in the hardest crystal or the heaviest metal, in short, matter of any kind, is permeated by a medium having the properties of a fluid of infinite tenuity called the *ether*. The particles of a heated body being in a state of intensely rapid vibration, communicate their motion to the ether around them, throwing it into a system of waves which travel through space and pass from one body to another with the velocity of light. When the undulations of the ether reach a given body, the motion is again delivered up to the particles of that body, which in turn begin to vibrate, that is, the body becomes heated. This passage of motion through the hypothetical ether is termed radiation, and a so called ray of heat is merely the direction of the motion of one series of waves.

It will facilitate the understanding of this to consider the analogous mode in which sound is produced and propagated. A sounding body is one whose entire mass is in a state of vibration; the more rapid the rate of vibration, the more acute the sound; the slower the rate of vibration, the deeper the sound. This vibratory motion is communicated to the surrounding air, by means of which the vibrations reach the auditory nerve and there produce the sensation of sound. If a metal ball be heated, say to the temperature of boiling water, we can ascertain that it radiates heat, although we cannot see any luminosity, and if its temperature be gradually raised we see it become successively of a dull red, bright red, and dazzling white. Here it is assumed that at each particular temperature the heated body emits waves of a definite length; in other words, its particles vibrate in a certain period. As its temperature rises it sends out other and more rapid undulations, which coexist however with all those which it had previously emitted. Thus the motion at each successive temperature is compounded of all preceding ones.

It has been seen that vibrations of the air below and above a certain rate do not affect the auditory nerve; it can only take up and transmit to the brain vibrations of a certain periodicity. So too with the vibrations

which produce heat. The optic nerve is insensible to a large number of wave lengths. It can apprehend only those waves that form the visible spectrum. If the rate of undulation be slower than the red or faster than the violet, though intense motion may pass through the humours of the eye and fall upon the retina, yet we shall be utterly unconscious of the fact, for the optic nerve cannot take up and respond to the rate of vibrations which exist beyond the visible spectrum in both directions. Hence these are termed *invisible* or *obscure* rays. A vast quantity of these obscure rays are emitted by flames which, though intensely hot, are yet almost non-luminous, such as the oxy-hydrogen flame or that of a Bunsen's burner; for the vibrations which these emit, though capable in part of penetrating the media of the eye, are incapable of exciting in the optic nerve the sensation of light.

391. **Thermal analysis of solar light.**—When a solar ray (fig. 306), admitted through an aperture in a dark room, is concentrated on a prism of rock salt by means of a lens of the same material, and then after

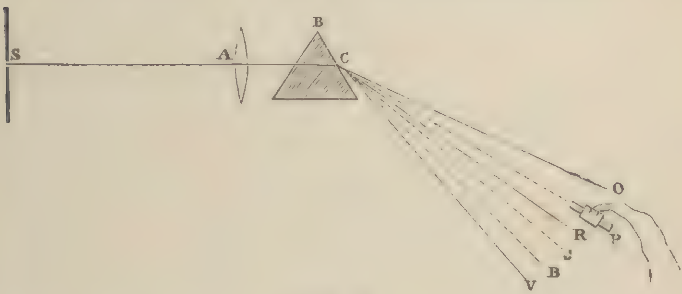


Fig. 306.

emerging from the prism is received on a screen, it will be found to present a band of colours in the following order: red, orange, yellow, green, blue, and violet. This is called the *spectrum.*

If now a narrow and delicate thermo-pile be placed successively on the space occupied by each of the colours, it will scarcely be affected on the violet, but in passing over the other colours it will indicate a gradual rise of temperature, which is greatest at the red. Painters thus, guided by a correct but unconscious feeling, always speak of blue and green colours as cold, and of red and orange as warm tones. If the pile be now moved in the same direction beyond the limits of the luminous spectrum, the temperature will gradually rise up to CP, at which it attains its maximum. From this point the pile indicates a decrease of temperature until it reaches a point O, where it ceases to be affected. This point is about as distant from R as the latter is from V; that is, there is a region in which thermal effects are produced extending as far beyond the red end of the spectrum in one direction as the entire length of the visible spectrum is in the other. In accordance with what we have stated the sun's light consists of rays of different rates of vibration; by their pas-

sage through the prism they are unequally broken or refracted ; those of greatest wave length or slowest vibrating period are least bent aside, or are said to be the least refrangible, while those with shorter wave lengths are the most refrangible.

These non-luminous rays outside the red are called the extra or ultra-red rays, or sometimes the *Herschelian* rays, from Sir W. Herschel, who first discovered their existence.

If in the above case prisms of other materials than rock salt be used, the position of maximum heat will be found to vary with the nature of the prism, a fact first noticed by Seebeck. Thus with a prism of water it is in the yellow ; with one of crown glass, in the middle of the red, and so on. These changes are due, as Melloni subsequently found, to the circumstances that prisms of different materials absorb rays of different refrangibility to unequal extents. But rock salt practically allows heats of all kinds to pass with equal facility, and thus gives a normal spectrum.

392. **Tyndall's researches.**—Prof. Tyndall has recently investigated the spectrum produced by the electric light, and has arrived at some highly important results. His mode of experimenting was as follows :— The electric light was produced between charcoal points by a Grove's battery of fifty cells. The beam, rendered parallel by a double rock salt lens, was caused to pass through a narrow slit, and then through a second lens of rock salt ; the slices of white light thus obtained being decomposed by a prism of the same material. To investigate the thermal conditions of the spectrum, a *linear* thermo-electric pile was used ; that is, one consisting of a number of elements arranged in a line, and in front of which was a slit that could be narrowed to any extent. The instrument was mounted on a movable bar connected with a fine screw, so that by turning a handle the pile could be pushed forward through the smallest space. On placing this apparatus, originally devised by Melloni for his researches on the solar spectrum, successively in each part of the spectrum of the electric light, the heating effected at various points near each other was determined by the indications of a very delicate galvanometer. As in the case of the solar spectrum, the heating effect gradually increased from the violet end towards the red, and was greatest in the dark space beyond the red. The position of the greatest heat was about as far from the limit of the visible red as the latter was from the green, and the total extent of the invisible spectrum was found to be twice that of the visible.

The increase of temperature in the dark space is very considerable. If thermal intensities are represented by perpendicular lines of proportionate length erected at those parts of the spectrum to which they correspond, on passing beyond the red end these lines increase rapidly and greatly in length, reach a maximum, and then fall somewhat more suddenly. If these lines are connected they form a curve (fig. 307), which beyond the red represents a massive peak, which quite dwarfs by its magnitude that of the visible spectrum. In fig. 308 the dark parts at the end represent the obscure radiation. The curve is based in the manner above stated, on the results obtained by Prof. Tyndall with the electric

light. The upper curve, in fig. 308, represents the spectrum of solar light from the experiments of Müller with a rock salt prism, while the lower curve represents the results obtained with the use of a flint glass prism, which is thus seen to absorb some of the ultra-red radiation.

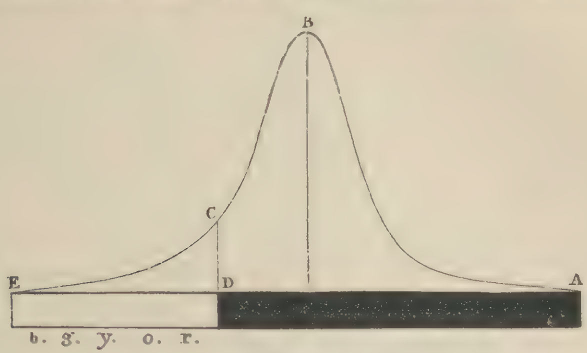


Fig. 307.

Prof. Tyndall found that by interposing various substances, more especially water, in certain thicknesses, in the path of the electric light, the ultra-red radiation was greatly diminished, the peak was not so lofty. Now aqueous vapour would, like water, absorb the obscure rays. And most probably the reason why the obscure part of the spectrum of the

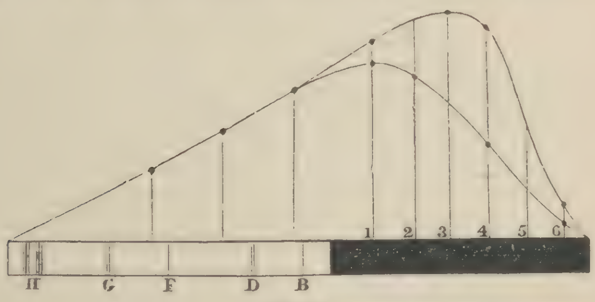


Fig. 308.

solar light is not so intense as in the case of the electric light, is that the obscure rays have been already partially absorbed by the aqueous vapour of the atmosphere. If a solar spectrum could be produced outside the atmosphere, it doubtless would give a spectrum more like that of the electric light, which is uninfluenced by the atmospheric absorption.

This has been remarkably confirmed in other ways. Melloni observed that the position of the maximum in the solar spectrum differs on different days ; which is probably due to the varying absorption of the atmosphere, in consequence of its varying hygrometric state. Recently, Secchi, in Rome, has found the same shifting of the maximum to occur

in the different seasons of the year; for in winter, when there is least moisture in the atmosphere, the maximum is farther from the red than in summer, when the aqueous vapour in the air is most abundant. An important observation on the luminous rays has also been made by Cooke, in America, who found that the faint black lines in the solar spectrum attributed to the absorption of light by our atmosphere (see book on Optics) are chiefly caused by the presence of aqueous vapour.

393. **Luminous and obscure radiation.**—It has been stated that the radiation from a luminous object, a gas flame for example, is of a composite character; a portion consists of what we term light, but a far greater part consists of heat rays, which are insensible to our eyes, being unable to affect the optic nerve. When this mixed radiation falls upon the blackened face of a thermo-electric pile, the whole of it is taken to be absorbed, the light by this act being converted into heat, and affecting the instrument proportionally with the purely calorific rays. The total radiation of a luminous source, expressed in units of heat or force, can thus be measured. By introducing into the path of the rays a body capable of stopping either the luminous or the obscure radiation, we can ascertain by the comparative action on the pile the relative quantities of heat and light radiated from the source. Melloni sought to do this by passing a luminous beam through a layer of water containing alum in solution; a liquid which he found in previous experiments absorbed all the radiation from bodies heated under incandescence. Comparing the transmission through this liquid—which allowed the luminous part of the beam to pass, but quenched the obscure portion—with the transmission through a plate of rock salt—which affected neither the luminous nor the obscure radiation, but gave the loss due to reflection—Melloni revealed the astonishing fact that 90 per cent. of the radiation from an oil flame and 99 per cent. of the radiation from an alcohol flame consist of invisible calorific rays. This proportion has been still further increased by the recent experiments of Prof. Tyndall, who employed a liquid free from the objections which have caused a slight error in Melloni's method. Prof. Tyndall discovered that iodine, whilst opaque to light, is transparent to the obscure heat rays. Dissolving this substance in bisulphide of carbon a solution was obtained which was impervious to the most intense light, but wonderfully pervious to radiant heat; only a slight absorption being effected by the bisulphide. By successively comparing the transmission through the transparent liquid, and the transmission through the same liquid rendered opaque by iodine, the value of the luminous radiation from various sources was found to be as follows:—

Source	Luminous	Obscure
Red-hot spiral	0	100
Hydrogen flame	0	100
Oil flame	3	97
Gas flame	4	96
White-hot spiral	4·6	95·4
Electric light	10	90

Here by direct experiment the ratio of luminous to obscure rays in the electric light is found to be 10 per cent. of the total radiation. By prismatic analysis, the curve shown in fig. 307 was obtained, graphically representing the proportion of luminous to obscure rays in the electric light; by calculating the areas of the two spaces in the diagram the obscure portion is found to be nearly 10 times as large as the luminous.

394. **Transmutation of obscure rays.**—We shall find, in speaking of the luminous spectrum, that beyond the violet there are rays which are invisible to the eye, but which are distinguished by their chemical action, and are spoken of as the *actinic* or chemical rays; they are also known as the *Ritteric* rays, from the philosopher who first discovered their existence.

As we shall also see in the book on Optics, Prof. Stokes has succeeded in converting these rays into rays of lower refrangibility, which then became visible; so Prof. Tyndall has recently effected the corresponding but inverse change, and has increased the refrangibility of the Herschelian or extra red rays, and thus rendered them visible.

Prof. Tyndall worked with the electric light. The charcoal points were placed in front of a concave silvered glass mirror in such a manner that the rays from the points after reflection were concentrated to a focus about 6 inches distant. On the path of the beam was interposed a cell full of a solution of iodine in bisulphide of carbon, which, as we have seen, has the power of completely stopping all luminous radiation, but gives free passage to the non-luminous rays. On now placing in the focus of the beam thus sifted a piece of platinum, this was raised to incandescence by the impact of perfectly invisible rays. In like manner a piece of charcoal in vacuo was heated to redness.

By a proper arrangement of the charcoal points a metal may be raised to whiteness, and the light now emitted by the metal yields on prismatic analysis a brilliant luminous spectrum, which is thus entirely derived from the invisible rays beyond the red.

To the new phenomena here described, this transmutation of non-luminous into luminous heat, Prof. Tyndall has applied the term *calorescence*.

When the eye was cautiously placed in the focus, guarded by a small hole being pierced in a metal screen, so that the converged rays should only enter the pupil and not affect the surrounding part of the eye, no impression of light was produced, and there was scarcely any sensation of heat. A considerable portion was absorbed by the humours of the eye, but yet a powerful beam undoubtedly reached the retina; for, as Prof. Tyndall showed by a separate experiment, about 18 per cent. of the obscure radiation from the electric light passed through the humours of an ox's eye.

395. **Transmutation of thermal rays.**—Melloni was the first who examined extensively and accurately the absorption of heat by solids and liquids. The apparatus he employed is represented in the annexed figure, 309, where AB is the thermo-electric pile; *a* is a support for the source of heat, in this case a Locatelli's lamp; F and E are screens, and

C is a support for the body experimented upon ; while *m* is the pile, and D the galvanometer.

The various sources of heat used by Melloni in his experiments have been already (389) enumerated.

To express the power which bodies have of transmitting heat, Melloni used the term *diathermancy* : diathermancy bears the same relation to radiant heat that transparency does to light ; and in like manner the power of stopping radiant heat is called *athermancy*, which thus corre-

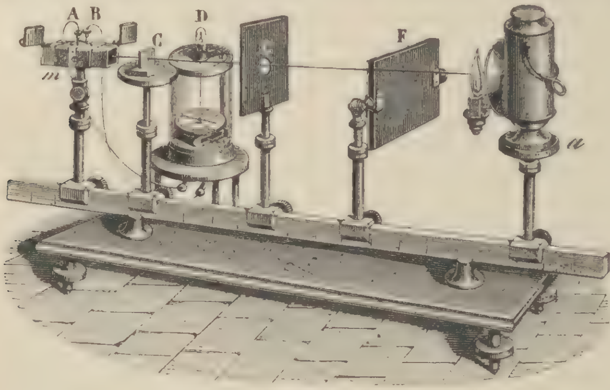


Fig. 309.

sponds to opacity for light. In experimenting on the diathermancy of liquids, Melloni used glass troughs with parallel sides, the thickness of the liquid layer being 0·36 in. The radiant heat of an Argand lamp with a glass chimney was first allowed to fall directly on the face of the pile, and the deflection produced in the galvanometer taken as the total radiation ; the substance under examination was then interposed, and the deflection noted. This corresponded to the quantity of heat transmitted by the substance. If t indicate this latter number, and t' the total radiation, then

$$t' : t :: 100 : x$$

which is the percentage of rays transmitted. Thus, calling the total radiation 100, Melloni found that

Bisulphide of carbon transmitted	. . . . .	63
Olive oil	,, ...	30
Ether	,, ...	21
Sulphuric acid	,, ...	17
Alcohol	,, ...	15
Solution of alum or sugar	,, ...	12
Distilled water	,, ...	11

In experimenting with solids the substances were cut into plates 0·1 inch in thickness, and it was found that of every 100 rays there was transmitted by

Rock salt	92	Selenite	20
Iceland spar and plate glass	62	Alum	12
Smoky quartz	57	Sulphate of copper	0
Transparent carbonate of lead	52		

The transmission of heat through liquids has been re-examined by Prof. Tyndall by a more perfect mode of experiment than that employed by Melloni. The experiments were made in the following way :—Instead of employing a glass vessel to hold the liquids under examination, he made use of a little cell whose ends were stopped by parallel plates of rock salt. The plates were separated by a ring of brass, with an aperture on the top through which the liquid could be poured. As this plate could be changed at will, liquid layers of various thicknesses were easily obtainable, the apparatus being merely screwed together and made liquid tight by paper washers. The instrument was mounted on a support before an opening in a brass screen placed in front of the pile. The source of heat employed was a spiral of platinum wire raised to incandescence by an electric current ; the spiral being enclosed in a small glass globe with an aperture in front through which the radiation passed unchanged in its character, a point of essential importance overlooked by Melloni. The following table contains the results of experiments made with liquids in the various thicknesses indicated, the numbers expressing the *absorption* per cent. of the total radiation. The *transmission* per cent. can be found in each case by subtracting the absorption from 100. Thus a layer of water 0·2 inch thick absorbs 80·7 and transmits 19·3 per cent. of the radiation from a red-hot spiral :

Absorption of heat by liquids.

Liquid	Thickness of liquid in parts of an inch				
	0·02	0·04	0·07	0·14	0·27
Bisulphide of carbon	5·5	8·4	12·5	15·2	17·3
Chloroform	16·6	25·0	35·0	40·0	44·8
Iodide of methyl	36·1	46·5	53·2	65·2	68·6
Iodide of ethyl	38·2	50·7	59·0	69·0	71·5
Benzole	43·4	55·7	62·5	71·5	73·6
Amylene	58·3	65·2	73·6	77·7	82·3
Ether	63·3	73·5	76·1	78·6	85·2
Acetic ether	—	74·0	78·0	82·0	86·1
Formic ether	65·2	76·3	79·0	84·0	87·0
Alcohol	67·3	78·6	83·6	85·3	89·1
Water	80·7	86·1	88·8	91·0	91·0

It appears from these tables, that there is no connection between diathermancy and transparency. The liquids, except olive oil, are all colourless and transparent, and yet vary as much as 75 per cent. in the amount of heat transmitted. Among the solids, smoky quartz, which is nearly opaque to light, transmits heat very well ; while alum, which is perfectly transparent, cuts off 88 per cent. of heat rays. As there are different

degrees of transparency, so there are different degrees of diathermancy: and the one cannot be predicated from the other.

By studying the transmission of heat from different parts of the spectrum separately the connection between light and heat becomes manifest. With this view Masson and Jamin received the spectrum of the solar light given by a prism of rock salt on a movable screen provided with an aperture, so that by raising or lowering the screen the action of any given part of the spectrum on different plates could be investigated. They thus found—

That glass, rock crystal, ice, and generally substances transparent for light, are also diathermanous for all kinds of *luminous* heat;

That a coloured glass, red, for instance, which only transmits the red rays of the spectrum and extinguishes the others, also extinguishes every kind of luminous heat, excepting that of the red rays;

That glass and rock crystal, which are diathermanous for luminous heat, also transmit the obscure heat near the red, that is, the most refrangible, but extinguish the extreme obscure rays, or those which are the least deflected by the prism.

Alum extinguishes a still greater proportion of the obscure spectrum, and ice stops it altogether.

396. **Influence of the nature of the heat.**—The diathermanous power differs greatly with the heat from different sources, as Melloni made evident from the following table, in which the numbers express what proportion of every 100 rays from the different sources of heat incident on the plates is transmitted:

	Locatelli's lamp	Incandescent platinum wire	Copper at 400°	Copper at 100°
Rock salt . . .	92	92	92	92
Fluor spar . . .	78	69	42	33
Plate glass . . .	39	24	6	0
Black glass . . .	26	25	12	0
Selenite . . .	14	5	0	0
Alum	9	2	0	0
Ice	6	0·5	0	0

These different sources of heat correspond to light from different sources. Rock salt is here stated to transmit all kinds of heat with equal facility, and to be the only substance which does so. It is analogous to white glass, which is transparent for light from all sources. Fluor spar transmits 78 per cent of the rays from a lamp, but only 33 of those from a blackened surface at 100°. A piece of plate glass only one-tenth of an inch thick and perfectly transparent to light, is opaque to all the radiation from a source at 100°, transmits only 6 per cent. of the heat from a source at 400°, and but 39 of the radiation from the lamp. Black glass, on the contrary, though it cuts off all heat from a source at 100°, allows 12 per cent. of the heat at 400° to pass, and is equally transparent to the heat from the spiral, but on account of its blackness is more opaque to the heat

from the lamp. As we have already seen, every luminous ray is a heat ray; now as several of the substances in this table are pervious to all the luminous rays, and yet, as in the case of ice, transmit but 6 per cent. of luminous heat, we have an apparent anomaly; which, however, is only a confirmation of the remarkably small proportion which the luminous rays of a lamp bear to the obscure.

From these experiments Melloni concluded that as the temperature of the source rose more heat was transmitted. This may be taken as a general law, which has been recently confirmed by some refined experiments of Prof. Tyndall. The platinum lamp, previously described, was used as the source, the temperature of which Prof. Tyndall was enabled to vary from a dark to a brilliant white heat, without disturbing in any way the position of the apparatus; the gradations of temperature being obtained by a gradual augmentation of the strength of the electric current which heated the platinum spiral. Instead of liquids, vapours were chosen as the subject of experiment, and examined in a manner to be described subsequently; the measurements are given in the following table:

Absorption of heat by vapours.

Name of vapour	Source, platinum spiral			
	Barely visible	Bright red	White hot	Near fusion
Bisulphide of carbon	6·5	4·7	2·9	2·5
Chloroform	9·1	6·3	5·6	3·9
Iodide of methyle	12·5	9·6	7·8	
Iodide of ethyle	21·3	17·7	12·8	
Benzole	26·4	20·6	16·5	
Amylene	35·8	27·5	22·7	
Ether	43·4	31·4	25·9	23·7
Formic ether	45·2	31·9	25·1	21·3
Acetic ether	49·6	34·6	27·2	

The percentage of rays absorbed is here seen to diminish in each case as the temperature of the source rises. Mere elevation of temperature does not, however, invariably produce a high penetrative power in the rays emitted; for Prof. Tyndall has shown that the rays from sources of far higher temperature than any of the foregoing are more largely absorbed by certain substances than are the rays emitted from any one of the sources as yet mentioned. Thus it was found that the radiation from a hydrogen flame was completely intercepted by a layer of water only 0·27 of an inch thick, the same layer transmitting 9 per cent. of the radiation from the red-hot spiral, a source of much lower temperature. The explanation of this is, that those rays which heated water emits (and water, the product of combustion, is the main radiant in a hydrogen flame) are the very ones which this substance most largely absorbs. This statement, which will become clearer after reading the analogous phenomena in the case of light, was strikingly exemplified by the powerful absorption of the

heat from a carbonic oxide flame by carbonic acid gas. It will be seen presently (399) that of the rays from a heated plate of copper olefiant gas absorbs 10 times the quantity intercepted by carbonic acid, whilst of the rays from a carbonic oxide flame Tyndall found carbonic acid absorbed twice as much as olefiant gas. A tenth of an atmosphere of carbonic acid enclosed in a tube 4 feet long, absorbs 60 per cent. of the radiation from a carbonic oxide flame. Radiant heat of this character can thus be used as a delicate test for the presence of carbonic acid, the amount of which can even be accurately measured by the same means. This has been done by Mr. Barrett, who, in this way, has made a *physical* analysis of the human breath. In one experiment the quantity of carbonic acid contained in breath physically analysed was found to be 4·56 per cent., whilst the same breath chemically analysed gave 4·66, a difference of only one-tenth per cent.

397. **Influence of the thickness and nature of screens.**—It will be seen from the table (396) that of every 100 rays rock salt transmits 92. The other 8 may either have been absorbed or reflected from the surface of the plate. According to Melloni, the latter is the case ; for if, instead of on one plate, heat be allowed to fall on two or more plates whose total thickness does not exceed that of the one, the quantity of heat arrested will be proportional to the number of reflecting surfaces. He therefore concluded rock salt to be quite diathermanous.

The experiments of MM. Provostaye and Desains, of Mr. Balfour Stewart, and those of Prof. Tyndall, show that this conclusion is not strictly correct ; rock salt does absorb a very small porportion of obscure rays.

The quantity of heat transmitted through rock salt is practically the same, whether the plate be 1, 2, or 4 millimeters thick. But with other bodies, absorption increases with the thickness, although by no means in direct proportion. This is seen to be the case in the table of absorption by liquids at different thicknesses. The following table tells what proportion of 1,000 rays from a Locatelli's lamp pass through a glass plate of the given thickness :

Thickness in millimeters .	0·5	1	2	3	4	5	6	7	8
Rays transmitted . .	775	733	682	653	634	620	609	600	592

The absorption takes place in the first layers ; the rays which have passed these possess the property of passing through other layers in a higher degree, so that beyond the first layers the heat transmitted approaches a certain. constant value. If a thin glass plate be placed behind another glass plate a centimeter thick, the former diminishes the transmission by little more than the reflection from its surface. But if a plate of alum were placed behind the glass plate, the result would be different, for the latter is opaque for much of the heat transmitted by glass.

Heat, therefore, which has traversed a glass plate traverses another plate of the same material with very slight loss, but is very greatly

diminished by a plate of alum. Of 100 rays which had passed through green glass or tourmaline, only 5 and 7 were respectively transmitted by the same plate of alum. A plate of blackened rock salt only transmits obscure rays, while alum extinguishes them. Consequently, when these two substances are superposed, a system impervious to light and heat is obtained.

These phenomena find their exact analogies in the case of light. The different sources of heat correspond to flames of different colours, and the various screens to glasses of different colours. A red flame looked at through a red glass appears quite bright, but through a green glass it appears dim or is scarcely visible. So in like manner heat which has traversed a red glass passes through another red glass with little diminution, but is almost completely stopped by a green glass.

Different luminous rays being distinguished by their *colours*, to these different obscure calorific rays Melloni gave the name of *thermocrosis* or heat colouration. The invisible portion of the spectrum is accordingly mapped out into a series of spaces, each possessing its own peculiar feature, corresponding to the coloured spaces which are seen in that portion of the spectrum visible to our eyes.

Besides thickness and colour, the polish of a substance influences the transmission. Glass plates of the same kind and thickness transmit more heat as their surface is more polished. Bodies which transmit heat of any kind very readily are not heated. Thus a window pane is not much heated by the strongest sun's heat ; but a glass screen held before a common fire stops most of the heat, and is itself heated thereby. The reason of this is that by far the greater part of the heat from a fire is obscure, and to this kind of heat glass is opaque.

398. **Diffusion of heat.**—When a ray of light falls upon an unpolished surface in a definite direction, it is decomposed into a variety of rays which are reflected from the surface in all directions. This irregular reflection is called *diffusion*, and it is in virtue of it that bodies are visible when light falls upon them. A further peculiarity is, that all solar rays are not equally diffused from the surface of bodies. Certain bodies diffuse certain rays and absorb others, and accordingly appear coloured. The red colour of a geranium is caused by its absorbing all the rays, excepting the red, which are irregularly reflected. Just as is the case with transmitted light in transparent bodies, so with diffused light in opaque ones, for if a red body is illuminated by red light it appears of a bright red colour, but if green light fall upon it it is almost black. We shall now see that here again analogous phenomena prevail with heat.

Various substances diffuse different thermal rays to a different extent ; each possesses a peculiar thermocrose or heat tint. Melloni placed a number of strips of brass foil between the source of heat and the thermopile. They were coated on the side opposite to the pile with lampblack, and on the other side with the substances to be investigated. Representing the quantity of heat absorbed by the lampblack at 100, the absorption of the other bodies was as follows :

	Incandescent platinum	Copper at 400°	Copper at 100°
Lampblack	100	100	100
White lead	56	89	100
Isinglass	54	64	91
Indian ink	95	87	85
Shellac	47	70	72
Polished metal	13·5	13	13

Hence, white lead absorbs far less of the heat radiated from incandescent platinum than lampblack, but it absorbs the obscure rays from copper at 100° as completely as lampblack. Indian ink is the reverse of this; it absorbs obscure rays less completely than luminous rays. Lampblack absorbed the heat from all sources in equal quantities, and very nearly completely. In consequence of this property all thermoscopes which are used for investigating radiant heat are covered with lampblack, as it is the best known absorbent of heat. The behaviour of metals is the reverse of that of lampblack. They reflect the heat of different sources in the same degree. They are to heat what *white* bodies are to light.

As coloured light is altered by diffusion from several bodies, so Knoblauch has shown that the different kinds of heat are altered by reflection from different surfaces. The heat of an Argand lamp diffused from white paper passes more easily through calcspar than when it has been diffused from black paper.

The rays of heat, like the rays of light, are susceptible of polarisation and double refraction. These properties will be better understood after treating of light.

399. **Relation of gases and vapours to radiant heat.**—For a long time it was believed that gaseous bodies were as permeable to heat as a vacuum; and though subsequently this was disproved, yet down to a recent period it was thought that whatever absorption such bodies might exercise was slight and similar in degree. The whole subject has, however, been investigated by Prof. Tyndall in a series of laborious experiments, which, with regard to the absorption of heat by gases, are of equal importance to those of Leslie, and afterwards of Melloni, in reference to solids and liquids.

The apparatus used in these experiments is represented, in its essential features, in the adjacent figure; the arrangement being looked upon from above.

A is a cylinder about 4 feet in length and 2½ inches in diameter, placed horizontally, the ends of which can be closed with rock salt plates: by means of a lateral tube at *r* it can be connected with an air pump and exhausted; while at *t* is another tube which serves for the introduction of gases and vapours. T is a sensitive thermo-pile connected with an extremely delicate galvanometer M.

The deflections of this galvanometer were proportional to the degrees of heat up to about 30°; beyond this point the proportionality no longer held good, and accordingly for the higher degrees a table was empirically

constructed, in which the value of the higher deflections was expressed in units; the unit being the amount of heat necessary to move the needle through one of the lower degrees.

C is a source of heat, which usually was either a Leslie's cube filled with boiling water, or else a sheet of blackened copper heated by gas.

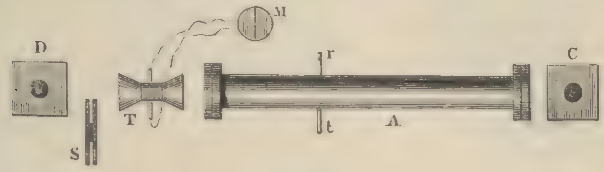


Fig. 310.

Now when the source of heat was permitted to radiate through the exhausted tube, it caused the needle to assume a very high deflection; and in this position a very considerable degree of absorption would have been needed to produce an alteration of 1° of the galvanometer. And if to lessen this deflection a lower source of heat had been used, the fraction absorbed would be correspondingly less, and might well have been insensible. Hence Prof. Tyndall adopted the following device, by which he was enabled to use a powerful flux of heat, and at the same time discover small variations in the quantity falling on the pile.

The source of heat at C was allowed to radiate through the tube at the end of which the pile was placed; a deflection was produced of, say 70°; a second source of heat, D, was then placed near the other face of the pile, the amount of heat falling on the pile from this *compensating* cube being regulated by means of a movable screen S. When both faces of the pile are warmed, two currents are produced, which are in opposite directions, and tending therefore to neutralise each other: when the heat on both faces is precisely equal the neutralisation is perfect, and no current at all is produced, however high may be the temperature on both sides. In the arrangement just described, by means of the screen S, the radiation from the compensating cube was caused to neutralise exactly the radiation from the source C; the needle consequently was brought down from 70° to zero, and remained there so long as both sources were equal. If now a gas or vapour be admitted into the exhausted tube, any power of absorption it may possess will be indicated by the destruction of this equilibrium, and preponderance of the radiation from the compensating cube, by an amount corresponding to the heat cut off by the gas. Examined in this way, air, hydrogen, and nitrogen, when dried by passing through sulphuric acid, were found to exert an almost inappreciable effect; their presence as regards radiant heat being but little different to a vacuum. But with olefiant and other complex gases the case was entirely different. Representing by the number 1 the quantity of radiant heat absorbed by air, olefiant gas absorbs 970 times, and ammoniacal gas 1195 times this amount. In the following table is given the absorption of obscure heat by various gases, referred to air as unity:

Name of gas	Absorption under 30 inches pressure
Air	1
Oxygen	1
Nitrogen	1
Hydrogen	1
Chlorine	39
Hydrochloric acid	62
Carbonic acid	90
Nitrous oxide	355
Marsh gas	403
Sulphurous acid	710
Olefiant gas	970
Ammonia	1195

If instead of comparing the gases at a common pressure of one atmosphere, they are compared at a common pressure of an inch, their differences in absorption are still more strikingly seen. Thus assuming the absorption by 1 inch of dry air to be 1, the absorption by inch of olefiant gas is 7,950, and by the same amount of sulphurous acid 8,800.

400. **Influence of pressure and thickness on the absorption of heat by gases.**—The absorption of heat by gases varies with the pressure; this variation cannot be seen in the case of air, as the total absorption is so small, but in the case of those gases which have considerable absorptive power it is easily shown. Taking the total absorption by atmospheric air under ordinary pressure at unity, the numbers of olefiant gas under a pressure of 1, 3, 5, 7, and 10 inches of mercury are respectively 90, 142, 168, 182, and 193. Thus one-thirtieth of an atmosphere of olefiant gas exerts 90 times the absorption of an entire atmosphere of air. And the absorption, it is seen, increases with the density, though not in a direct ratio. Prof. Tyndall showed, however, by special experiments, that for very low pressures the absorption does increase with the density. Employing as a unit volume of the gas a quantity which measured only $\frac{1}{50}$ of a cubic inch, and admitting successive measures of olefiant gas into the experimental tube, it was found that up to 15 measures the absorption was directly proportionate to the density in each case.

In these experiments the length of the experimental tube remained the same whilst the pressure of the gas within it was caused to vary: in other subsequent experiments the pressure of the gas was kept constant, whilst the length of the tube was, by suitable means, varied from 0·01 of an inch up to 50 inches. The source was a heated plate of copper; of the total radiation from this nearly 2 per cent. were absorbed by a film of olefiant gas ·01 of an inch thick, upwards of 9 per cent. by a layer of the same gas 0·1 of an inch thick, 33 per cent. by a layer 2 inches thick, 68 per cent. by a column 20 inches long, and 77 per cent. by a column rather more than 4 feet long.

401. **Absorptive power of vapours.**—Great as is the absorptive power of olefiant gas, it is exceeded, as Prof. Tyndall found, by that of several vapours. The mode of experimenting was analogous to that with

the gases. The liquid from which the vapours were to be derived was enclosed in a small flask, which could be attached with a stopcock to the exhausted experimental tube. The absorption was then determined after admitting the vapours into the tube in quantities measured by the pressure of the barometer gauge attached to the air pump.

The following table shows the absorption of vapours under pressures varying from 0·1 to 1·0 inch of mercury.

Name of vapours	Absorption under pressures in inches of mercury		
	0·1	0·5	1·0
Bisulphide of carbon	15	47	62
Benzole	66	182	267
Chloroform	85	182	236
Ether	300	710	870
Alcohol	325	622	
Acetic ether	590	980	1195

These numbers refer to the absorption of a whole atmosphere of dry air as their unit, and it is thus seen that a quantity of bisulphide of carbon vapour, the feeblest absorbent yet examined, which only exerts a pressure of $\frac{1}{10}$ of an inch of mercury, or the $\frac{1}{300}$ of an atmosphere, gave 15 times the absorption of an entire atmosphere of air; and $\frac{1}{10}$ of an inch of acetic ether 590 times as much. Comparing air at a pressure of 0·1 with acetic ether of the same pressure, the absorption of the latter would be more than 17,500 times as great as that of the former.

The absorption by the infinitesimally small quantity of matter constituting a perfume can never be measured; for Prof. Tyndall found that the odours from the essential oils exercised a marked influence on radiant heat. Perfectly dry air was allowed to pass through a tube containing dried paper impregnated with various essential oils, and then admitted into the experimental tube. Taking the absorption of dry air as unity, the following were the numbers respectively obtained for air scented with various oils:—Patchouli 31, otto of roses 37, lavender 60, thyme 68, rosemary 74, cassia 109, aniseed 372. Thus the perfume of a flower-bed absorbs a large percentage of the heat of low refrangibility emitted from it.

Ozone prepared by electrolysing water was also found to have a remarkable absorptive effect. The small quantity of ozone present in electrolytic oxygen was found in one experiment to exercise 136 times the absorption of the entire mass of the oxygen itself.

But the most remarkable, perhaps, and certainly the most important results which Prof. Tyndall has obtained are those which follow from his very numerous experiments on the behaviour of aqueous vapour to radiant heat. The experimental tube was filled with air, dried as perfectly as possible, and the absorption it exercised was found to be one unit. Exhausting the tube, and admitting the ordinary undried, but not specially moist, air from the laboratory, the absorption now rose to 72 units. This difference between dried and undried air can only be ascribed to the aqueous vapour the latter contains. Thus on a day of average humidity the absorptive effect due to the transparent aqueous

vapour present in the atmosphere is 72 times as great as that of the air itself, though in quantity the latter is about 200 times greater than the former. Analogous results were obtained on different days, and with specimens of air taken from various localities. When air which had been specially purified was allowed to pass through a tube filled with fragments of moistened glass and examined, it was found to exert an absorption 90 times that of pure air.

In some other experiments Prof. Tyndall suppressed the use of rock salt plates in his experimental tube, and even the tube itself, and yet in every case the results were such as to show the great power which aqueous vapour possesses as an absorbent of radiant heat.

The absorptive action which the aqueous vapour in the atmosphere exerts on the sun's heat has been established by a series of actinometrical observations made by Soret at Geneva and on the summit of Mont Blanc; he finds that the intensity of the solar heat on the top of Mont Blanc is $\frac{6}{5}$ of that at Geneva; in other words, that of the heat which is radiated at the height of Mont Blanc, about $\frac{1}{5}$ is absorbed in passing through a vertical layer of the atmosphere 14.436 feet in thickness. The same observer has found that with virtually equal solar heights there is the smallest radiation on those days on which the tension of aqueous vapour is greatest, that is, when there is most moisture in the atmosphere.

402. **Radiating power of gases.**—Prof. Tyndall also examined the *radiating* power of gases. A red-hot copper ball was placed so that the current of heated air which rose from it acted on one face of a thermo-pile: this action was compensated by a cube of hot water placed in front of the opposite face. On then allowing a current of dry olefiant gas from a gasholder to stream through a ring burner over the heated ball and thus supplant the ascending current of hot air, it was found that the gas radiated energetically. By comparing in this manner the action of many gases it was discovered that, as is the case with solids, those gases which are the best absorbers are also those which radiate most freely.

403. **Dynamic radiation and absorption.**—To another class of phenomena which Prof. Tyndall discovered he gives the name, *dynamic radiation and absorption.*

A gas when permitted to enter an exhausted tube is heated in consequence of the collision of its particles against the sides of the vessel; it thus becomes a source of heat, which is perfectly capable of being measured. Prof. Tyndall calls this *dynamic heating*. In like manner, when a tube full of gas or vapour is rapidly exhausted, a chilling takes place owing to the loss of heat in the production of motion. This Prof. Tyndall calls *dynamic chilling or absorption.*

He could thus determine the radiation or absorption of a gas without any source of heat external to the gas itself. An experimental tube was taken, one end of which was closed with a polished metal plate, and the other with a plate of rock salt; in front of the latter was the face of the pile. The needle being at zero, and the tube exhausted, a gas was allowed quickly to enter until the tube was full, the effect on the galvanometer

being noted. This being only a transitory effect the needle soon returned to zero; the tube was then rapidly pumped out, by which a sudden chilling was produced, and the needle exhibited a deflection in the opposite direction.

Comparing in this way the dynamic heating and chilling of various gases, it was found that those gases which are the best absorbers are in like manner the best radiators.

Metallic surfaces when polished are, as we have seen (386), bad radiators, but radiate freely when covered with varnish. Now Prof. Tyndall made the curious experiment of varnishing a metallic surface by a film of gas. A Leslie's cube was placed with its polished metal side in front of the pile, and its effect neutralised by a second cube placed before the other face of the pile. On allowing, by a special arrangement, a stream of olefiant or coal gas to flow from a gasholder over the metallic face of the first cube, a copious radiation from that side was produced as long as the flow of gas continued. Acting on the principle indicated in the foregoing experiment, Prof. Tyndall determined the dynamic radiation and absorption of vapours. The experimental tube containing a vapour under a small known pressure, air was allowed to enter until the pressure inside the tube was the same as that of the atmosphere. In this way the entering air by its impact against the tube became heated; and its particles mixing with those of the minute quantity of vapour present, each of them became, so to speak, coated with a layer of the vapour. The entering air was in this case a source of heat, just as in the above experiments the Leslie cube was. Here, however, one gas varnished another; the radiation and subsequently the absorption of various vapours could thus be determined.

It was found that vapours differed very materially in their power of radiating under these circumstances: of those which were tried bisulphide of carbon vapour was the worst and boracic ether the best radiator. And in all cases those which were the best absorbents were also the best radiators. By this method Prof. Tyndall was able to observe a definite radiative power with the more powerful vapours when the quantity present was immeasurably small.

404. **Relation of absorption to molecular state.**—Up to a recent period it was considered that the absorption of heat was mainly dependent upon the physical condition of the body examined. This led to the belief that it was impossible for substances of such tenuity as gases and vapours to absorb any sensible amount of heat; and that the absorption by bodies when in a liquid state would be unlike the same bodies when solid; moreover, that if all solid bodies were reduced to an equally fine state of division, the present differences in their absorbent and radiative powers would disappear. A few experiments made by Melloni on atmospheric air supported the first idea, and a series of experiments by Masson and Courtepée established the belief in the last. But we have seen that Prof. Tyndall's researches have revealed the powerful absorption of heat by various gases and vapours, and we shall now briefly show that the researches of the same philosopher have overthrown the last two

conclusions, giving us an insight into the cause of the absorption of heat which before was unattainable.

After the examination of the absorption of heat by vapours, Prof. Tyndall tried the same substances in a liquid form. The conditions of the experiments were in both cases the same; the source of heat was always a spiral of platinum, heated to redness by an electric current of known strength; and plates of rock salt were invariably employed to contain both vapours and liquids. Finally, the absorption by the vapours was remeasured; in this case introducing into the experimental tube, not as before equal quantities of vapour, but amounts proportional to the density of the liquid. When this last condition had been attained, it was found that the order of absorption by a series of liquids, and by the same series when turned into vapour, was precisely the same. Thus the substances tried stood in the following order as liquid and as vapour, beginning with the feeblest absorbent, and ending with the most powerful:—

Liquids.	Vapours.
Bisulphide of carbon	Bisulphide of carbon.
Chloroform	Chloroform.
Iodide of methyl	Iodide of methyl.
Iodide of ethyl	Iodide of ethyl.
Benzole	Benzole.
Amylene	Amylene.
Sulphuric ether	Sulphuric ether.
Acetic ether	Acetic ether.
Formic ether	Formic ether.
Alcohol	Alcohol.
Water.	

A direct determination of the proportional amount of the vapour of water could not be made, on account of the lowness of its tension, and the hygroscopic nature of the plates of the rock salt. But the remarkable and undeviating regularity of the absorption by all the other substances in the list, when as liquid and vapour, establishes the fact, which is corroborated by the experiments we have already mentioned, that aqueous vapour is one of the most energetic absorbents of heat.

In this table it will be noticed that those substances which have the simplest chemical constitution stand first in the list, with one anomalous exception, namely, that of water. In the absorption of heat by gases, Prof. Tyndall found that the elementary gases were the feeblest absorbents, while the gases of most complex constitution were the most powerful absorbers. These facts, which were found in a general way to be true for solids, liquids, and gases, have led Prof. Tyndall to infer that absorption is mainly dependent on chemical constitution; that is to say, that absorption and radiation are molecular acts independent of the physical condition of the body.

But this conclusion appeared to be contradicted by the experiments of Masson and Courtepée on powders. Prof. Tyndall has therefore repeated these experiments, and found them to be entirely incorrect. Avoiding

the source of error into which the French experimenters had fallen, Tyndall has discovered that the radiation of powders is similar to that of the solids from which they were derived, and therefore differs greatly *inter se*. The absorbent power of powders was also found to correspond with their radiative power—as we have shown to be the case with solids and gases, and, though as yet we have no experiments on the subject, is doubtless also true for liquids. The powders were attached to the tin surfaces of a Leslie's cube, in such a manner that radiation took place from the surface of the powder alone. The following table gives the radiation in units from some of the powders examined by Tyndall; the metal surface of the cube giving a deflection of 15 units.

Radiation from powders.

Rock salt	35·3	Sulphate of calcium	77·7
Biniodide of mercury	39·7	Red oxide of iron	78·4
Sulphur	40·6	Hydrated oxide of zinc	80·4
Chloride of lead	55·4	Black oxide of iron	81·3
Carbonate of calcium	70·2	Sulphide of iron	81·7
Red oxide of lead	74·2	Lampblack	84·0

It will be noticed that these substances are of various colours. Some are white, such as rock salt, chloride of lead, carbonate and sulphate of calcium, and hydrated oxide of zinc; some are red, such as biniodide of mercury and oxide of lead; whilst others are black, as sulphide of iron and lampblack: we have besides other colours. The colours therefore have no influence on the radiating power: for example, rock salt is the feeblest radiator, and hydrated oxide of zinc one of the most powerful radiators. The views of Prof. Tyndall therefore, instead of being overthrown, were confirmed by these his latest experiments.

Nearly a century ago Franklin made experiments on coloured pieces of cloth, and found their absorption, indicated by their sinking into snow on which they were placed, to increase with the darkness of the colour. But all the cloths were equally powerful absorbents of obscure heat, and the effects noticed were only produced by their relative absorptions of light. In fact, the conclusion to be drawn from Franklin's experiment only holds good for luminous heat, especially sunlight, such as he employed.

405. **Applications.**—The property which bodies possess of absorbing, emitting, and reflecting heat, meets with numerous applications in domestic economy and in the arts. Leslie stated in a general manner that white bodies reflect heat very well, and absorb very little, and that the contrary is the case with black substances. As we have seen, this principle is not generally true, as Leslie supposed; for example, for non-luminous rays white lead has as great an absorbing power as lampblack (398). Leslie's principle applies to powerful absorbents like cloth, cotton, wool, and other organic substances when exposed to luminous heat. Accordingly, the most suitable coloured clothing for summer is just that which experience has taught us to use, namely, white, for it absorbs less of the sun's rays than black clothing, and hence feels cooler.

The polished fire-irons before a fire are cold, whilst the black fender is often unbearably hot. If, on the contrary, a liquid is to be kept hot as long as possible, it must be placed in a brightly polished metallic vessel, for then, the emissive power being less, the cooling is slower. It is for this reason advantageous that the steam pipes, etc., of locomotives should be kept bright.

In the Alps, the mountaineers accelerate the fusion of the snow by covering it with earth, which increases the absorbing power.

In our dwellings, the outsides of the stoves and of hot-water apparatus ought to be black, and the insides of fire-places ought to be lined with fire-clay, in order to increase the radiating power towards the apartment.

It is in consequence of the great diathermaneity of dry atmospheric air that the higher regions of the atmosphere are so cold, notwithstanding the great heat which traverses them : whilst the intense heat of the sun's direct rays on high mountains is probably due to the comparative absence of aqueous vapour at those high elevations.

As nearly all the luminous rays of the sun pass through water, and the sun's radiation as we receive it on the surface of the earth consisting of a large proportion of luminous rays, accidents have often arisen from the convergence of these luminous rays by bottles of water which act as lenses. In this way gunpowder could be fired by the heat of the sun's rays concentrated by a water lens; and the drops of water on leaves in greenhouses have, it is said, been found to act as lenses, and burn the leaves on which they rest.

Certain bodies can be used (395) to separate the heat and light radiated from the same source. Rock salt covered with lampblack, or still better with iodine, transmits heat, but completely stops light. On the other hand, alum, either as a plate or in solution, or a thin layer of water, is permeable to light, but stops all the heat from obscure sources. This property is made use of in apparatus which are illuminated by the sun's rays, in order to sift the rays of their heating power, and a vessel full of water or a solution of alum is used with the electric light when it is desirable to avoid too intense a heat.

In gardens, the use of shades to protect plants depends partly on the diathermancy of glass for heat from luminous rays and its athermancy for obscure rays. The heat which radiates from the sun is largely of the former quality, but by contact with the earth it is changed into obscure heat, which as such cannot retraverse the glass. This explains the manner in which greenhouses accumulate their warmth, and also the great heat experienced in summer in rooms having glass roofs, for the glass in both cases effectually entraps the solar rays. On the same principle plates of glass are frequently used as screens to protect us from the heat of a fire : the glass allows us to see the cheerful light of the fire, but intercepts the larger part of the heat radiated from the fire. Though the screens thus become warm by the heat they have absorbed, yet as they radiate this heat in all directions, towards the fire as well as towards us, we finally receive less heat when they are interposed.

CHAPTER IX.

CALORIMETRY.

406. **Calorimetry. Thermal unit.**—The object of calorimetry is to measure the *quantity of heat* which a body parts with or absorbs when its temperature sinks or rises through a certain number of degrees, or when it changes its condition.

Quantities of heat may be expressed by any of its directly measurable effects, but the most convenient is the alteration of temperature, and quantities of heat are usually defined by stating the extent to which they are capable of raising a known weight of a known substance, such as water.

The unit chosen for comparison, and called the *thermal unit*, is not everywhere the same. In France it is the quantity of heat necessary to raise the temperature of *one* kilogramme of water through *one* degree Centigrade; this is called a *calorie*. In this book we shall adopt, as a thermal unit, *the quantity of heat necessary to raise one pound of water through one degree Centigrade*: 1 *calorie* = 2·2 thermal units, and 1 thermal unit = 0·45 *calorie*.

407. **Specific heat.**—When equal weights of two different substances at the same temperature placed in similar vessels are subjected for the same length of time to the heat of the same lamp, or are placed at the same distance in front of the same fire, it is found that their temperatures will vary considerably; the mercury will be much hotter than the water. But as, from the conditions of the experiment, they have each been receiving the same amount of heat, it is clear that the quantity of heat which is sufficient to raise the temperature of mercury through a certain number of degrees will only raise the temperature of the same quantity of water through a less number of degrees; in other words, that it requires more heat to raise the temperature of water through one degree than it does to raise the temperature of mercury by the same extent. Conversely, if the same quantities of water and of mercury at 100° C. be allowed to cool down to the temperature of the atmosphere, the water will require a much longer time for the purpose than the mercury: hence, in cooling through the same number of degrees, water gives out more heat than does mercury.

It is readily seen that all bodies have not the same specific heat. If a pound of mercury at 100° is mixed with a pound of water at zero, the temperature of the mixture will only be about 3°. That is to say, that while the mercury has cooled through 97°, the temperature of the water has only been raised 3°. Consequently the same weight of water requires about 32 times as much heat as mercury does to produce the same elevation of temperature.

If similar experiments are made with other substances it will be found that the quantity of heat required to effect a certain change of temperature is different for almost every substance, and we speak of the *specific*

heat or *calorific capacity* of a body as the quantity of heat which it absorbs when its temperature rises through a given range of temperature, from zero to 1° for example, compared with the quantity of heat which would be absorbed under the same circumstances, by the same weight of water. In other words, water is taken as the standard for the comparison of specific heats. Thus, to say that the specific heat of lead is 0·0314, means that the quantity of heat which would raise the temperature of any given quantity of lead through 1° C. would only raise the temperature of the same quantity of water through 0·0314.

Three methods have been employed for determining the specific heats of bodies : (i.) the method of the melting of ice, (ii.) the method of mixtures, and (iii.) that of cooling. In the latter, the specific heat of a body is determined by the time which it takes to cool through a certain temperature. Previous to describing these methods it will be convenient to explain the expression for the quantity of heat absorbed or given out by a body of known weight and specific heat, when its temperature rises or falls through a certain number of degrees.

408. **Measure of the sensible heat absorbed by a body.**—Let m be the weight of a body in pounds, c its specific heat, and t its temperature. The quantity of heat necessary to raise a pound of water through one degree being taken as unity, m of these units would be required to raise m pounds of water through one degree, and to raise it through t degrees, t times as much, or mt. As this is the quantity of heat necessary to raise through t degrees m pounds of water whose specific heat is unity, a body of the same weight, but of different specific heat, would require mtc. Consequently, when a body is heated through t degrees, the quantity of heat which it absorbs is *the product of its weight into its temperature into its specific heat*. This principle is the basis of all the formulæ for calculating specific heats.

If a body is heated or cooled from t' to t degrees, the heat absorbed or disengaged will be represented by the formula

$$m(t'-t)c, \text{ or } m(t-t')c.$$

A thorough comprehension of these formulæ will prevent any difficulty in the solution of problems on specific heat.

409. **Method of the fusion of ice.**—This method of determining specific heats is based on the fact that to melt a pound of ice 80 thermal units are necessary, or more exactly 79·25. Black's calorimeter (fig. 311) consists of a block of ice in which a cavity is made, and which is provided with a cover of ice. The substance whose specific heat is to be determined is heated to a certain temperature, and then placed in the cavity which is covered. After some time the body becomes cooled to zero. It is then opened, and both the substance and the cavity wiped dry with a cloth

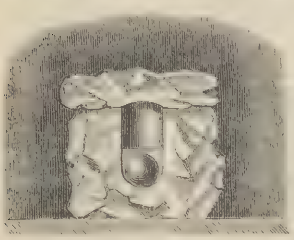


Fig. 311.

which has been previously weighed. The increase of weight of this cloth obviously represents the ice which has been converted into water.

Now, since one pound of ice at 0° in melting to water at 0° absorbs 80 thermal units, P pounds absorbs 80 P units. On the other hand, this quantity of heat is equal to the heat given out by the body in cooling from $t°$ to zero, which is mtc, for it may be taken for granted that in cooling from $t°$ to zero a body gives out as much heat as it absorbs in being heated from zero to $t°$. Consequently, from

$$mtc = 80\text{ P we have } c = \frac{80\text{P}}{mt}.$$

It is difficult to obtain blocks of ice as large and pure as those used by Black in his experiments, and Lavoisier and Laplace have replaced the block of ice by a more complicated apparatus, which is called the *ice calorimeter*. Fig. 312 gives a perspective view of it, and fig. 313 represents a section. It consists of three concentric tin vessels; in the central one is placed the body M, whose specific heat is to be determined, while

Fig. 312.

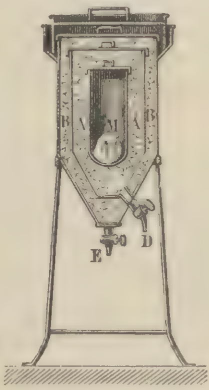


Fig. 313.

the two others are filled with pounded ice. The ice in the compartment A is melted by the heated body, while the ice in the compartment B cuts off the heating influence of the surrounding atmosphere. The two stopcocks E and D give issue to the water which arises from the liquefaction of the ice.

In order to find the specific heat of a body by this apparatus, its weight m is first determined; it is then raised to a given temperature, t, by keeping it for some time in an oil or water bath, or in a current of steam. Having been quickly brought into the central compartment, the lids are replaced and covered with ice, as represented in the figure. The water which flows out by the stopcock D is collected. Its weight, P, is manifestly that of the melted ice. The calculation is then made as in the preceding case.

There are many objections to the use of this apparatus. From its size it requires some quantity of ice, and a body, M, of large mass; while the experiment lasts a considerable time. A certain weight of the melted water remains adhering to the ice, so that the water which flows out from D does not exactly represent the weight of the melted ice.

410. **Method of mixtures.**—In determining the specific heat of a solid body by this method, it is weighed and raised to a known temperature, by keeping it, for instance, for some time in a closed space heated by steam; it is then immersed in a mass of cold water, the weight and temperature of which are known. From the temperature of the water after mixture the specific heat of the body is determined.

Let M be the weight of the body, T its temperature, c its specific heat; and let m be the weight of the cold water, and t its temperature.

As soon as the heated body is plunged into the water, the temperature of the latter rises until both are at the same temperature. Let this temperature be θ. The heated body has been cooled by $T-\theta$; it has, therefore, lost a quantity of heat, $M(T-\theta)c$. The cooling water has, on the contrary, absorbed a quantity of heat equal to $m(\theta-t)$, for the specific heat of water is unity. Now the quantity of heat given by the body is manifestly equal to the quantity of heat absorbed by the water; that is, $M(T-\theta)c=m(\theta-t)$, from which

$$c=\frac{m(\theta-t)}{M(T-\theta)}$$

An example will illustrate the application of this formula. A piece of iron weighing 60 ounces, and at a temperature of 100° C., is immersed in 180 ounces of water, whose temperature is 19° C. After the temperatures have become uniform, that of the cooling water is found to be 22° C. What is the specific heat of the iron?

Here the weight of the heated body M is 60, the temperature T is 100°, c is to be determined; the temperature of mixture, θ, is 22°, the weight of the cooling water is 180, and its temperature 19°. Therefore,

$$c=\frac{180(22-19)}{60(100-22)}=\frac{9}{78}=0{\cdot}1153$$

411. **Corrections.**—The vessel containing the cooling water is usually a small cylinder of silver or brass, with thin polished sides, and is supported by some badly-conducting arrangement. It is obvious that this vessel, which is originally at the temperature of the cooling water, shares its increase of temperature, and in accurate experiments this must be allowed for. The decrease of temperature of the heated body is equal to the increase of temperature of the cooling water, and of the vessel in which it is contained. If the weight of this latter be m', and its specific heat c', its temperature, like that of the water, is t: consequently the previous equation becomes

$$Mc(T-\theta)=m(\theta-t)+m'c'(\theta-t)$$

from which, by obvious transformations,

$$c=\frac{(m+m'c')(\theta-t)}{M(T-\theta)}$$

Generally speaking, the value $m' c'$ is put $=\mu$; that is to say, μ is the weight of water which would absorb the same quantity of heat as the vessel. This is said to be the *reduced value* in water of the vessel, or the *water equivalent.* The expression accordingly becomes

$$c=\frac{(m+\mu)\ (\theta-t)}{M(T-\theta)}.$$

In accurate experiments it is necessary also to allow for the heat absorbed by the glass and mercury of the thermometer, by introducing into the equation their values reduced on this principle.

In order to allow for the loss of heat due to radiation, a preliminary experiment is made with the body whose specific heat is sought, the only object of which is to ascertain approximately the increase of temperature of the cooling water. If this increase be 10°, for example, the temperature of the water is reduced by half this number—that is to say 5° below the temperature of the atmosphere—and the experiment is then carried out in the ordinary manner.

By this method of compensation, first introduced by Rumford, the water receives as much heat from the atmosphere during the first part of the experiment as it loses by radiation during the second part.

412. **Regnault's apparatus for determining specific heats.**—Fig. 314 represents one of the forms of apparatus used by M. Regnault in determining specific heats by the method of mixtures.

The principal part is a water-bath, AA, of which fig. 315 represents a section. It consists of three concentric compartments; in the central one there is a small basket of brass wire, *c*, containing fragments of the substance to be determined, in the middle of which is placed a thermometer, T. The second compartment is heated by a current of steam coming through the tube *e*, from a boiler, B, and passing into a worm, *a*, where it is condensed. The third compartment, *ii*, is an air chamber, to hinder the loss of heat. The water bath AA rests on a chamber, K, with double sides, EE, forming a jacket, which is kept full of cold water, in order to exclude the heat from AA and from the boiler B. The central compartment of the water bath is closed by a damper, *r*, which can be opened at pleasure, so that the basket *c* can be lowered into the chamber K.

On the left of the figure is represented a small and very thin brass vessel, D, suspended by silk threads on a small carriage, which can be moved out of, or into, the chamber K. This vessel, which serves as a calorimeter, contains water, in which is immersed a thermometer, *t*. Another thermometer at the side, *t'*, gives the temperature of the air.

When the thermometer T shows that the temperature of the substance in the bath is stationary, the screen *h* is raised, and the vessel D moved to just below the central compartment of the water bath. The damper *r* is then withdrawn, and the basket *c* and its contents are lowered into the water of the vessel D, the thermometer T remaining fixed in the cork. The carriage and the vessel D are then moved out, and the water agitated until the thermometer T becomes stationary. The temperature which

it indicates is θ. This temperature known, the rest of the calculation is made in the manner described in art. 411, care being taken to make all the necessary corrections.

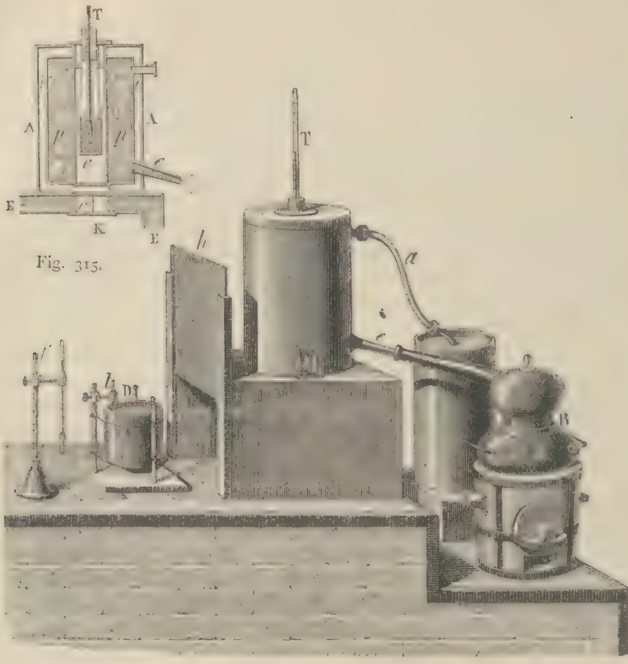


Fig. 315.

Fig. 314.

In determining the specific heat of substances—phosphorus, for instance—which could not be heated without causing them to melt, or undergo some change which would interfere with the accuracy of the result, Regnault adopted an inverse process : he cooled them down to a temperature considerably below that of the water in the calorimeter, and then observed the diminution in the temperature of the latter, which resulted from immersing the cool substance in it.

To ascertain the specific heat of bodies, such as potassium, where the use of water is quite inapplicable, the determination is made in another liquid, such as turpentine or benzole, the specific heat of which is known.

413. **Method of cooling.**—Equal weights of different bodies whose specific heats are different, will occupy different times in cooling through the same number of degrees. Dulong and Petit have applied this principle in determining the specific heats of bodies in the following manner : A small polished silver vessel is filled with the substance in a state of fine powder, and a thermometer placed in the powder, which is pressed down,

This vessel is heated to a certain temperature, and is then introduced into a copper vessel, in which it fits hermetically. This copper vessel is exhausted, and maintained at the constant temperature of melting ice, and the time noted which the substance takes in falling through a given range of temperature, from 15° to 5° for example. The times which equal weights of different bodies require for cooling through the same range of temperature are directly as their specific heats.

Regnault has proved that with solids this method does not give trustworthy results; it assumes, which is not quite the case, that the cooling in all parts is equal, and that all substances part with their heat to the silver case with equal facility. The method may, however, be employed with success in the determination of the specific heat of liquids.

414. **Specific heat of liquids.**—The specific heat of liquids may be determined either by the method of cooling, by that of mixtures, or by that of the ice calorimeter. In the latter case they are contained in a small metal vessel, or a glass tube, which is placed in the compartment E (fig. 313), and the experiment then made in the usual manner.

It will be seen from the following table that water and oil of turpentine have a much greater specific heat than that of other substances, and more especially than the metals. It is from its great specific heat that water requires a long time in being heated or cooled, and that for the same weight and temperature it absorbs or gives out far more heat than other substances. This double property is applied in the hot water apparatus, of which we shall presently speak, and it plays a most important part in the economy of nature.

415. **Mean specific heats of solids and liquids between 0° and 100°.**—By means of the method of mixture and of that of cooling, M. Regnault has determined the specific heats of a number of bodies. The following table contains the numbers obtained for the bodies usually met with in the arts:

Substances	Specific heats	Substances	Specific heats
Water	1·00000	Nickel	0·10863
Turpentine	0·42590	Cobalt	0·10696
Calcined animal charcoal	0·26085	Zinc	0·09555
Wood charcoal	0·24111	Copper	0·09515
Sulphur	0·20259	Brass	0·09391
Graphite	0·20187	Silver	0·05701
Thermometer glass	0·19768	Tin	0·05623
Phosphorus	0·18949	Antimony	0·05077
Diamond	0·14687	Mercury	0·03332
Grey iron	0·12983	Gold	0·03244
Steel	0·11750	Platinum	0·03244
Iron	0·11379	Bismuth	0·03084

These numbers represent the mean specific heats between 0° and 100°. Dulong and Petit's investigations have, however, shown that the specific heats increase with the temperature. Those of the metals, for instance, are greater between 100° and 200° than between zero and 100°, and are

still greater between 200° and 300°. That is to say, a greater amount of heat is required to raise a body from 200° to 250° than from 100° to 150°, and still more than from zero to 50°. For silver, the mean specific heat between 0° and 100° is 0·0557, while between 0° and 200° it is 0·0611. The specific heat of platinum for any temperature may be expressed by the formula $0·0328 + 0·0000042t$, where t is the temperature; and that of water by the formula $1 + 0·00004t + 0·0000009t^2$.

The increase of specific heat with the temperature is greater as bodies are nearer their fusing point. Any action which increases the density and molecular aggregation of a body, diminishes its specific heat. The specific heat of copper is diminished by its being hammered, but it regains its original value after the metal has been again heated.

The specific heat of a liquid increases with the temperature much more rapidly than that of a solid. Water is, however, an exception; its specific heat increases less rapidly than does that of solids.

A substance in the liquid state has a greater specific heat than when it is solid; thus, melted tin has the specific heat 0·0637, while that of solid tin is only 0·05623. The specific heat of liquid bromine is 0·111, that of solid bromine being 0·081. The difference in the case of water is greater. Its specific heat is 1, that of ice, according to Person, being 0·504. In the gaseous state a body has a higher specific heat than in the liquid state.

Pouillet used the specific heat of platinum for measuring high degrees of heat. Supposing 200 ounces of platinum had been heated in a furnace, and had then been placed in 1000 ounces of water, the temperature of which it had raised from 13° to 20°. From the formula we have $M = 200$, $m = 1000$; θ is 20, and t is 13. The specific heat of platinum is 0·033, and we have, therefore, from the equation,

$$Mc(T - \theta) = m(\theta - t)$$

$$T = \frac{m(\theta - t) + Mc\theta}{Mc} = \frac{7000 + 132}{6·6} = \frac{7132}{6·6} = 1080°$$

It is found, however, that the specific heat of platinum at temperatures of about 1000° is 0·0373; if this value, therefore, be substituted for c in the above equation,

$$T = \frac{7159·2}{7·46} = 958° \text{C}.$$

By this method, which requires great skill in the experimenter, Pouillet determined a series of high temperatures. He found, for example, the temperature of melting iron to be 1500° to 1600° C.

416. **Dulong and Petit's law.**—A knowledge of the specific heat of bodies has become of great importance, in consequence of Dulong and Petit's discovery of the remarkable law, that the product of the specific heat of any element into its atomic weight is a constant number, a law which may also be enunciated by saying that *the specific heats of simple bodies are inversely as their atomic weights.* Thus, taking the atomic weight of iron at 28, its specific heat 0·11379, and the product 3·186; the

atomic weight of nickel is 29·5, its specific heat 0·10863, product 3·204; the atomic weight of hydrogen is 1, its specific heat 3·2, and the product is 3·2.

Regnault, who determined the specific heats of a large number of elements with great care, confirmed Dulong and Petit's law, but he found that the number, instead of being constant, as Dulong and Petit had supposed, varies between 2·95 and 3·41. These variations may depend partly on the difficulty of obtaining the elements quite pure, and partly on the errors incidental to the determinations of the specific heats, and of the equivalents. But the specific heats of bodies vary with the state of aggregation, and also with the limits of the temperature at which they are determined. Some, such as potassium, have been determined at temperatures very near their fusing points; others, like platinum, at great distances from these points. And, doubtless, the principal reason of the discrepancies is the fact that the determinations have not been made under identical physical conditions, and at temperatures equally distant from the fusing point.

The equivalents of the elements represent the relative weights of equal numbers of atoms of these bodies, and the product pc of the specific heat c into the equivalent p is the *atomic specific heat*, or the quantity of heat necessary to raise the temperature of the same number of atoms by one degree; and Dulong and Petit's law may be thus expressed: *the same quantity of heat is needed to heat an atom of all simple bodies to the same extent.*

The atomic heat of a body, when divided by its specific heat, gives the equivalent of a body. Regnault has even proposed to use this relation as a means of determining the equivalent, and it certainly is of great service in deciding on the equivalent of a body in cases where the chemical relations permit a choice between two or more numbers.

In compound bodies the law also prevails; the product of the specific heat into the equivalent is an almost constant number, which varies, however, with the different classes of bodies. Thus, for the class of oxides of the general formula RO, it is 11·30; for the sesquioxides R^2O^3, it is 27·15; for the sulphides RS, it is 18·88; and for the carbonates RCO^3, it is 21·54.

The law may be expressed in the following general manner: *With compounds of the same formula, and of a similar chemical constitution, the product of the atomic weight into the specific heat is a constant quantity.* This includes Dulong and Petit's law as a particular case.

417. **Specific heat of compound bodies.**– In order to deduce the specific heat of the compound from that of its elements, M. Wœstyn has made the following hypothesis: he assumes that an element, in entering into combination with others to form a compound body, retains its own specific heat, so that if $p, p,' p''$, ... represent the atomic weights of the elements, and P that of the compound; c, c', c'', ... C., the corresponding specific heats, while n, n', n'', ... are the numbers of atoms of these simple bodies which make up the molecule of the compound, the relation obtains:

$$PC = npc + n'p'c' + n''p''c'' + \ldots$$

M. Wœstyn has found that the results obtained by calculating, on this hypothesis, the specific heats of the sulphides, iodides, and bromides, agree with experimental results.

418. **Specific heat of gases.**—The specific heat of a gas may be referred either to that of water or to that of air. In the former case, it represents the quantity of heat necessary to raise a given weight of the gas through one degree, as compared with the heat necessary to raise the same weight of water one degree. In the latter case it represents the quantity of heat necessary to raise a given volume of the gas through one degree, compared with the quantity necessary for the same volume of air treated in the same manner.

De la Roche and Berard determined the specific heats of gases in reference to water by causing known volumes of a given gas under constant pressure, and at a given temperature, to pass through a spiral glass tube placed in water. From the increase in temperature of this water, and from the other data, the specific heat was determined by a calculation analogous to that given under the method of mixtures. The same physicists also determined the specific heats of different gases relatively to that of air, by comparing the quantities of heat which equal volumes of a given gas, and of air at the same pressure and temperature, imparted to equal weights of water. Subsequently to these researches, De la Rive and Marcet have applied the method of cooling to the same determination; and still more recently Regnault has made a series of investigations on the calorific capacities of gases and vapours, in which he has adopted, but with material improvements, the method of De la Roche and Bernard. He has thus obtained the following results for the specific heats of the various gases and vapours, compared first with an equal weight of water taken as unity; secondly, with that of an equal volume of air, referred, as before, to its own weight of water taken as unity.

		Specific heats	
		Equal weights	Equal volumes
	Air	0·2374	0·2374
Simple gases	Oxygen	0·2175	0·2405
	Nitrogen	0·2438	0·2370
	Hydrogen	3·4090	0·2359
	Chlorine	0·1210	0·2962
Compound gases	Binoxide of nitrogen	0·2315	0·2406
	Carbonic oxide	0·2450	0·2370
	Carbonic acid	0·2163	0·3307
	Hydrochloric acid	0·1845	0·2333
	Ammonia	0·5083	0·2966
	Olefiant gas	0·4040	0·4106
Vapours	Water	0·4805	0·2984
	Ether	0·4810	1·2296
	Alcohol	0·4534	0·7171
	Turpentine	0·5061	2.3776
	Bisulphide of carbon	0·1570	0·4140
	Benzole	0·3754	1·0114

In making these determinations the gases were under a constant pressure, but variable volume; that is, the gas as it was heated could expand, and this is called the *specific heat under constant pressure*. But if the gas when being heated is kept at a constant volume, its pressure or elastic force then necessarily increasing, it has a different capacity for heat; this latter is spoken of as the *specific heat under constant volume*. That this latter is less than the former is evident from the following considerations: Suppose a given quantity of gas to have had its temperature raised $t°$, while the pressure remained constant, this increase of temperature will have been accompanied by a certain increase in volume. Supposing now that the gas is so compressed as to restore it to its original volume, the result of this compression will be to raise its temperature again to a certain extent, say $t'°$. The gas will now be in the same condition as if it had been heated, and not been allowed to expand. Hence, the same quantity of heat which is required to raise the temperature of a given weight of gas, $t°$, while the pressure remains constant and the volume alters, will raise the temperature $t+t'$ degrees if it is kept at a constant volume but variable pressure. The specific heat, therefore, of a gas at constant pressure, $c_{\prime}$, is greater than the specific heat under constant volume, c, and they are to each other as $t+t' : t$, that is $\frac{c_{\prime}}{c} = \frac{t+t'}{t}$.

It is not possible to determine by direct means the specific heat of gases under constant volume with even an approach to accuracy; and it has always been determined by some indirect method, of which the most accurate is based on the theory of the propagation of sound (214). The latest determination made on this basis gives the number 1·414 for the value of $\frac{c_{\prime}}{c}$.

419. **Latent heat of fusion.**—Black was the first to observe that during the passage of a body from the solid to the liquid state, a quantity of heat disappears, so far as thermometric effects are concerned, and which is accordingly said to become latent.

In one experiment he suspended in a room at the temperature 8°·5 two thin glass flasks, one containing water at 0°, and the other the same weight of ice at 0°. At the end of half an hour the temperature of the water had risen 4°, that of the ice being unchanged, and it was 10½ hours before the ice had melted and attained the same temperature. Now the temperature of the room remained constant, and it must be concluded that both vessels received the same amount of heat in the same time. Hence 21 times as much heat was required to melt the ice and raise it to 4° as was sufficient to raise the same weight of water through 4°. So that the total quantity of heat imparted to the ice was $21 \times 4 = 84$, and as of this only 4 was used in raising the temperature, the remainder, 80, was used in simply melting the ice.

He also determined this latent heat by immersing 119 parts of ice at 0° in 135 parts of water at 87·7° C. He thus obtained 254 parts of water at 11·6° C. Taking into account the heat received by the vessel in which

the liquid was placed, he obtained the number 79·44 as the latent heat of liquidity of ice.

We may thus say:

Water at 0° = ice at 0° + latent heat of liquefaction.

The method which Black adopted is essentially that which is now used for the determination of latent heats of liquids ; it consists in placing the substance under examination at a known temperature in the water (or other liquid) of a calorimeter, the temperature of which is sufficient to melt the substance if it is solid, and to solidify it if liquid, and when uniformity of temperature is established in the calorimeter, this temperature is determined. Thus, to take a simple case, suppose it is required to determine the latent heat of liquidity of ice. Let M be a certain weight of ice at zero, and m a weight of water at $t°$ sufficient to melt the ice. The ice is immersed in the water, and as soon as it has melted the final temperature $\theta°$ is noted. The water, in cooling from $t°$ to $\theta°$ has parted with a quantity of heat, $m(t-\theta)$. If x be the latent heat of the ice, it absorbs, in liquefying, a quantity of heat, Mx ; but, besides this, the water which it forms has risen to the temperature $\theta°$, and to do so has required a quantity of heat, represented by Mθ. We thus get the equation

$$Mx + M\theta = m(t-\theta)$$

from which the value of x is deduced.

By this method, and avoiding all sources of error, MM. Desains and De la Provostaye found that the latent heat of the liquefaction of ice is 79·25 ; that is, a pound of ice, in liquefying, absorbs the quantity of heat which would be necessary to raise 79·25 pounds of water, 1°, or, what is the same thing, one pound of water from zero to 79·25°.

This method is thus essentially that of the method of mixtures ; the same apparatus may be used, and the same precautions are required in the two cases. In determining the latent heat of liquidity of most solids, the different specific heats of the substance require to be taken into account. In such a case, let m be the weight of the water in the calorimeter (the water equivalents of the calorimeter and thermometer supposed to be included) ; M the weight of the substance operated on ; t the original and θ the final temperature of the calorimeter ; T the original temperature of the substance ; $\mathfrak{T}$ its melting (or freezing) point ; C the specific heat of the substance in the solid state between the temperature $\mathfrak{T}$ and θ ; c its specific heat in the liquid state between the temperatures T and $\mathfrak{T}$; and let L be the latent heat sought.

If the experiment is made on a melted substance which gives out heat to the calorimeter and solidifies it (it is taken for granted that a body gives out as much heat in solidifying as it absorbs in liquefying), it is plain that the quantity of heat absorbed by the calorimeter, $m(\theta-t)$, is made up of three parts: first, the heat lost by the substance in cooling from its original temperature T to the solidifying point $\mathfrak{T}$; secondly, the heat given out in solidification, L ; and, thirdly, the heat it loses in sinking from its solidifying point $\mathfrak{T}$ to the temperature of the water of the calorimeter. That is:

$$m(\theta-t)=\mathrm{M}\Big[(\mathrm{T}-\mathfrak{T})c+\mathrm{L}+(\mathfrak{T}-\theta)\mathrm{C}\Big]$$

whence,

$$\mathrm{L}=\frac{m(\theta-t)}{\mathrm{M}}-(\mathrm{T}-\mathfrak{T})c-(\mathfrak{T}-\theta)\mathrm{C}.$$

M. Person, who has made several researches on this subject, has obtained the following numbers for the latent heats of fusion of several bodies:

Water	79·24	Bismuth	12·64
Nitrate of sodium	62·97	Sulphur	9·37
Zinc	28·13	Lead	5·37
Silver	21·07	Phosphorus	5·03
Tin	14·25	D'Arcet's alloy	4·50
Cadmium	13·66	Mercury	2.83

These numbers represent the number of degrees through which a pound of water would be raised by a pound of the body in question in passing from the liquid to the solid state ; or, what is the same thing, the number of pounds of water that would be raised 1° C. by one of the bodies in solidifying.

420. **Determination of the latent heat of vapours.**—Liquids, as we have seen, in passing into the state of vapour, absorb a very considerable quantity of heat, which is termed *latent heat of vaporisation*. In determining the heat absorbed in liquids, it is assumed that a vapour, in liquefying, gives out as much heat as it had absorbed in becoming converted into vapour.

The method employed is essentially the same as that for determining the specific heat of gases. Fig. 316 represents the apparatus used by M. Despretz. The vapour is produced in a retort, C, where its temperature is indicated by a thermometer. It passes into a worm immersed in cold water, where it condenses, imparting its latent heat to the condensing water in the vessel B. The condensed vapour is collected in a vessel, A, and its weight represents the quantity of vapour which has passed through the worm. The thermometers in B give the change of temperature.

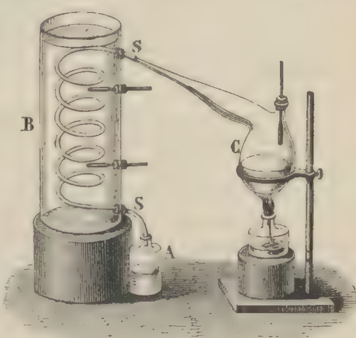


Fig. 316.

Let M be the weight of the condensed vapour, T° its temperature on entering the worm, which is that of its boiling point, and x the latent heat of vaporisation. Similarly let m be the weight of the condensing water (comprising the weight of the vessel B and of the worm SS *reduced* in water), let t° be the temperature of the water at the beginning and θ° its temperature at the end of the experiment.

It is to be observed that, at the commencement of the experiment, the condensed vapour passes out at the temperature $t°$, while at the conclusion its temperature is $\theta°$; we may, however, assume that its mean temperature during the experiment is $\frac{(t+\theta)}{2}$. The vapour M after condensation has therefore parted with a quantity of heat $M\left(T-\frac{t+\theta}{2}\right)\theta c$, while the heat disengaged in liquefaction is represented by Mx. The quantity of heat absorbed by the cold water, the worm and the vessel is $m(\theta-t)$. Therefore,

$$Mx + M - \left(T - \frac{t+\theta}{2}\right)c = m(\theta - t)$$

from which x is obtained. M. Despretz found that the latent heat of aqueous vapour at 100° is 540; that is, a pound of water at 100° absorbs in vaporising as much heat as would raise 540 pounds of water through 1°. M. Regnault found the number 537, and MM. Favre and Silbermann 538·8.

As in the case of the latent heat of water we may say,

Steam at 100° = Water at 100° + latent heat of gascification.

421. **Favre and Silbermann's calorimeter.**—The apparatus (fig. 317) furnishes a very delicate means of determining the calorific capacity of liquids, latent heats of evaporation, and the heat disengaged in chemical actions.

The principal part is a spherical iron reservoir, A, full of mercury, of which it holds about 50 pounds, and represents, therefore, a volume of more than half a gallon. On the left there are two tubulures, B, in which are fitted two sheet iron tubes or *muffles*, projecting into the interior of the bulb. Each can be fitted with a glass tube for containing the substance experimented upon. In most cases one muffle and one glass tube are enough; the two are used when it is desired to compare the quantities of heat produced in two different operations. In a third vertical tubulure, C, there is also a muffle, which can be used for determining calorific capacities by Regnault's method (410), in which case it is placed beneath the r of fig. 314.

The tubulure d contains a steel piston; a rod, turned by a handle, m, and which is provided with a screw thread, transmits a vertical motion to the piston; but, by a peculiar mechanism, gives it no rotatory motion. In the last tubulure is a glass bulb, a, in which is a long capillary glass tube, bo, divided into parts of equal capacity.

It will be seen from this description that the mercury calorimeter is nothing more than a thermometer with a very large bulb and a very capillary stem: it is therefore very delicate. It differs, however, from a thermometer in the fact that the divisions do not indicate the temperature of the mercury in the bulb, but the number of thermal units imparted to it by the substances placed in muffle.

This graduation is effected as follows:—By working the piston the mercury can be made to stop at any point of the tube, bo, at which it is

desired the graduation should commence. Having then placed in the iron tube a small quantity of mercury, which is not afterwards changed, a thin glass tube, *e*, is inserted, which is kept fixed against the buoyancy of the mercury by a small wedge not represented in the figure. The tube being thus adjusted, the point of a bulb tube (see fig. 318) is introduced containing water, which is raised to the boiling point: turning the position of the pipette, then, as represented on n', a quantity of the liquid flows into the test tube.

The heat which is thus imparted to the mercury makes it expand; the

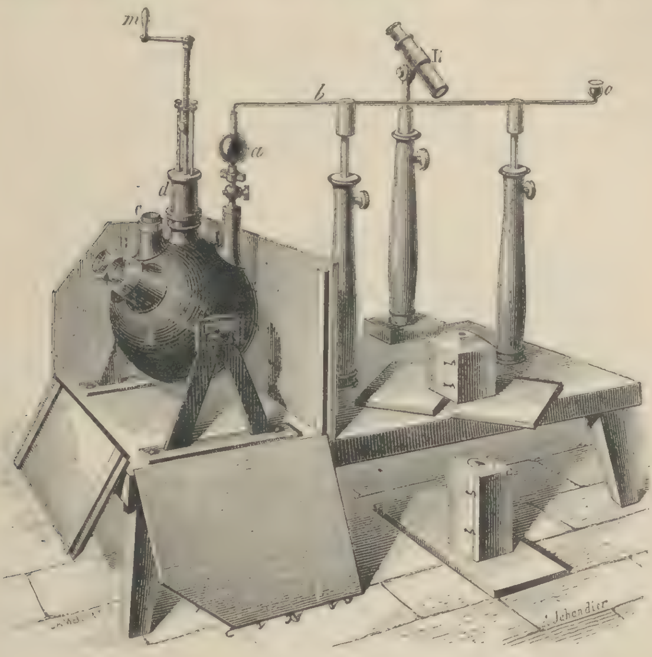


Fig. 317.

column of mercury in *bo* is lengthened by a number of divisions, which we shall call n. If the water poured into the test glass be weighed, and if its temperature be taken when the column *bo* is stationary, the product of the weight of the water into the number of degrees through which it has fallen indicates the number of thermal units which the water gives up to the entire apparatus (408). Dividing by n this number of thermal units, the quotient gives the number a of thermal units corresponding to a single division of the tube *bo*.

In determining the specific heat of liquids, a given weight, M, of the liquid in question is raised to the temperature T, and is poured in the tube C. Calling the specific heat of the liquid C, its final temperature θ,

and n the number of divisions by which the mercurial column bo has advanced, we have,

$$Mc(T-\theta)=na, \text{ from which } c=\frac{na}{M(T-\theta)}.$$

The boards represented round the apparatus are hinged so as to form a box, which is lined with eider down or wadding to prevent any loss of

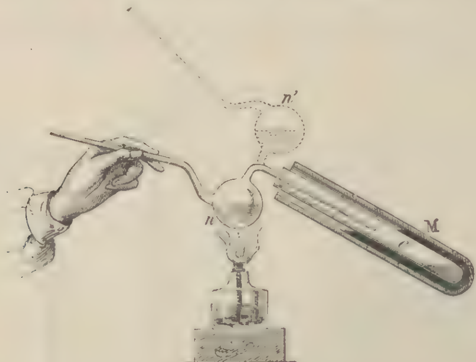


Fig. 318.

heat. It is closed at the top by a board, which is provided with a suitable case also lined, which fit over the tubulures d and a. A small magnifying glass which slides along the latter enables the divisions on scale to be read off.

422. **Examples.**—I. What weight of ice at zero must be mixed with 9 pounds of water at 20° in order to cool it to 5°?

Let M be the weight of ice necessary; in passing from the state of ice to that of water at zero, it will absorb 80M thermal units; and in order to raise it from zero to 5°, 5M thermal units will be needed. Hence the total heat which it absorbs is $80M + 5M = 85M$. On the other hand, the heat given up by the water in cooling from 20° to 5° is $9 \times (20-5) = 135$. Consequently,

$$85M = 135 \text{ ; from which } M = 1{\cdot}588 \text{ pounds.}$$

II. What weight of steam at 100° is necessary to raise the temperature of 208 pounds of water from 14° to 32°?

Let p be the weight of the steam. The latent heat of steam is 540°, and consequently p pounds of steam in condensing into water give up a quantity of heat, $540p$, and form p pounds of water at 100°. But the temperature of the mixture is 32°, and therefore p gives up a further quantity of heat $p(100-32)=68p$, for in this case c is unity. The 208 pounds of water in being heated from 14° to 32° absorb $208(32-14)=3744$ units. Therefore,

$$540p + 68p = 3744 \text{ ; from which } p = 6{\cdot}158 \text{ pounds.}$$

CHAPTER X.

STEAM ENGINES.

423. **Steam engines.**—*Steam engines* are machines in which the elastic force of aqueous vapour is used as motive force. In the ordinary engines the alternate expansion and condensation of steam imparts to a piston an alternating rectilinear motion, which is changed into a circular motion by means of various mechanical arrangements.

Every steam engine consists essentially of two distinct parts: the apparatus in which the vapour is produced, and the engine proper. We shall first describe the former.

424. **Steam boiler.**—The boiler is the apparatus in which steam is generated. Fig. 319 represents a cylindrical boiler, such as is commonly

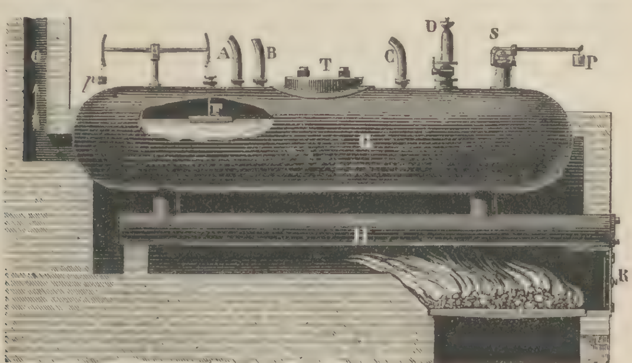


Fig. 319.

used in France, and which, in this country, is known as the *French boiler*. Boilers of this kind are used for a fixed engine; those of locomotives and of steam vessels are very different.

It is a long wrought iron cylinder, with hemispherical ends, beneath which there are two smaller cylinders of the same material, and communicating with the boiler by two tubes. Only one of these cylinders is represented in the figure. They are called *heaters*, and are quite full of water, while the boiler is only about half full.

Below these heaters is the fire. The smoke and heated air, after having circulated about the heaters and the boilers, escape into the atmosphere by means of a high chimney.

Explanation of figure 319.

A. Tube which conducts the steam to the tube, *c*, of the *valve chest* (fig. 421).

B. Tube by which the steam passes to a manometer or *pressure gauge*, which indicates the pressure of vapour in the boiler.

C. Feed pipe of the boiler.

D. *Safety whistle*—so called because it gives a whistle when there is not water enough in the boiler, a circumstance which might produce an accident. As long as the level of the water is not too low in the boiler, the vapour does not pass into the whistle, but if the level sinks below a certain point, a small float, which is not represented in the figure, and which closes the bottom of the whistle, sinks, and the steam escapes ; in so doing it grazes against the edge of a metallic plate, which it sets in vibration, and produces the sharp sound. This steam whistle is the sound heard frequently on railways ; it is used as a signal in locomotives.

F. *Float*, to indicate the level of the water in the boiler. It consists of a rectangular piece of stone, partially immersed in water, as seen through the space represented as left open. This stone, which is suspended at one end of a lever, is kept poised by the loss of weight which it sustains by immersion in water, and by a weight, *p*, at the other end of the lever. As long as the water is at the desired height, the lever which sustains the float remains horizontal, but it sinks when there is too little water, and rises in the contrary direction when there is too much. Guided by these indications, the stoker can regulate the supply of water.

G. Cylindrical wrought iron *boiler*.

H. *Heaters*, opposite each other.

O. Chimney.

P. Weight which loads the safety valve.

p. Counterpoise of the float.

R. Fire door.

S. *Safety valve*, described under Papin's digester (336).

T. *Man-hole*, an aperture by which the boiler can be repaired and cleaned.

425. **Double action, or Watt's engine.**—In the *double acting steam engine*, the steam acts alternately above and below the piston. It is also known as *Watt's engine*, from its illustrious inventor.

We shall first give a general idea of this engine, and shall then describe each part separately. On the left of the fig. 320 is the *cylinder* which receives the steam from the boiler. A part of its side is represented as being left open, and a piston, P, can be seen which is moved alternately up and down by the pressure of the steam above or below the piston. By the piston rod A this motion is transmitted to a huge iron lever, L, called the *beam*, which is supported by four iron columns. The beam transmits its motion to a *connecting rod*, I, working on a crank, K, to which it imparts a continuous rotatory motion. The crank is fixed to a horizontal *shaft*, which turns with it, and by means of wheels or endless bands, this shaft sets in motion various machines, such as spinning frames, saw mills, lathes, &c.

On the left of the cylinder is a valve chest, where, by a mechanism, which will presently be described, the steam passes alternately above and below the piston. Now, after its action on either face of the piston

it must disappear, for otherwise a pressure would be exerted in two opposite directions, and the piston would remain at rest. To effect this, the steam, after it has acted on one side of the piston, passes into a vessel, O, called the *condenser*, into which cold water is injected. It is almost completely condensed there, and consequently, the pressure ceases in that part of the cylinder which is in communication with the condenser, and as there is now pressure on only one face of the piston, it either rises or sinks.

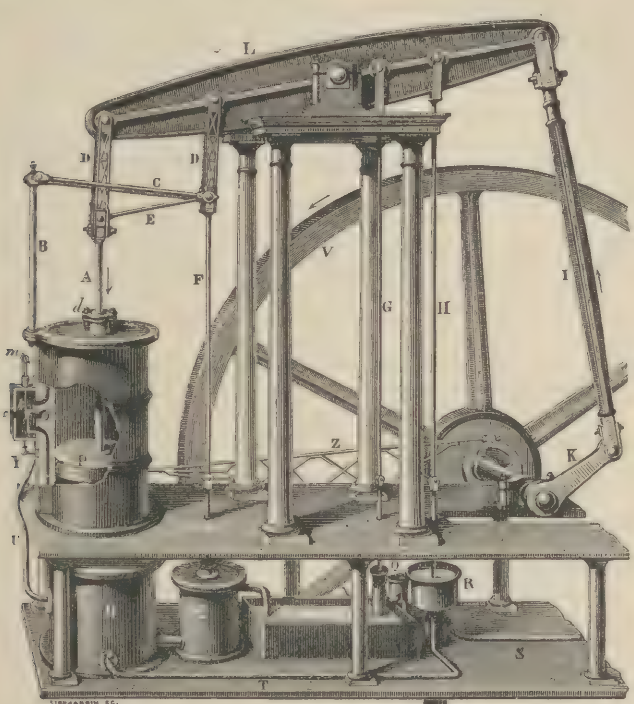


Fig. 320.

The use of the condenser depends upon Watt's law of vapours (327), that when two vessels communicating with each other, and containing saturated vapour, are at different temperatures, the tension is the same in both vessels, and is that corresponding to the temperature of the colder vessel.

The injected water is rapidly heated by the condensation of the steam, and must be constantly renewed. This is effected by means of two pumps ; one, M, is called the *air pump*, and pumps, from the condenser, the heated water which it contains, and also the air which was dissolved in the water of the boiler, and which passes with the stream into

the cylinder and condenser; the other, R, is called the *cold water pump*, and forces cold water from a well, or from a river, into the condenser.

A third pump, Q, which is called the *feed pump*, utilises the heated water by forcing it from the condenser into the boiler.

Double action steam engine.

A. *Piston rod* connected with a parallel motion, and serving to transmit to the beam the upward and downward motion of the piston.

B. Rod fixed to the cylinder, or elsewhere, and supporting the guiding arm or radius rod, C.

C. Double guiding arm directing the parallel motion.

DDDE. Rods forming at the end of the beam a *parallel motion*, to which is fixed the piston rod, and the object of which is to guide the motion of this rod in a straight line.

F. Rod of the *air pump*, which removes from the condenser the air and heated water which it contains.

G. Rod of the *feed pump*, which forces into the boiler through the tube S the heated water pumped from the condenser.

H. Rod of the *cold water pump*, which supplies the cold water necessary for condensation.

I. *Connecting rod*, which transmits the motion of the beam to the crank.

K. *Crank*, which imparts the motion of the rod to the horizontal shaft.

L. *Beam*, which moves on an axle in its middle, and transmits the motion of the piston to the connecting rod I.

M. Cylinder of the air pump, in connection with the condenser O.

N. Reservoir for the heated water pumped by the air pump from the condenser.

O. Condenser into which cold water is injected, to condense the steam after it has acted on the piston.

P. *Metallic piston*, moving in a cast-iron cylinder; this piston receives the direct pressure of the steam, and transmits the motion to all parts of the machine.

Q. Feeding force pump, which sends the water into the boiler.

R. Cold water pump.

S. Pipe by which the hot water from the feed-pump passes into the boiler.

T. Pipe by which cold water from the reservoir of the pump, R, passes into the condenser.

U. Pipe by which the steam from the cylinder passes into the condenser after acting on the piston.

V. Large iron wheel, called the *fly wheel*, which, by its inertia, serves to regulate the motion, especially when the piston is at the top or bottom of its course, and the crank K at its *dead points*.

Y. Bent lever which imparts the motion of the eccentric *c* to the slide valve *b*.

Z. Eccentric rod.

a. Aperture which communicates both with the upper and lower part of the cylinder, according to the position of the slide valve, and by which steam passes into the condenser through the tube U.

b. Rod transmitting motion to the *slide valve*, by which steam is alternately admitted above and below the piston. This will be described in greater detail in the next article.

c. Aperture by which steam reaches the valve chest.

d. Stuffing box, in which the piston rod works without giving exit to the steam.

e. Eccentric, fixed to the horizontal shaft, and rotating in a collar, to which the rod Z is attached.

m. Rod which connects the rod of the slide valve *b* to the bent lever Y, and to the eccentric.

The lower part of the figure does not exactly represent the usual arrangement of the pumps. The drawing has been modified in order more clearly to show how these parts work, and their connection with each other.

426. **Distribution of the steam. Eccentric.**—Figure 321 represents the details of the *valve chest* or arrangement for the *distribution of*

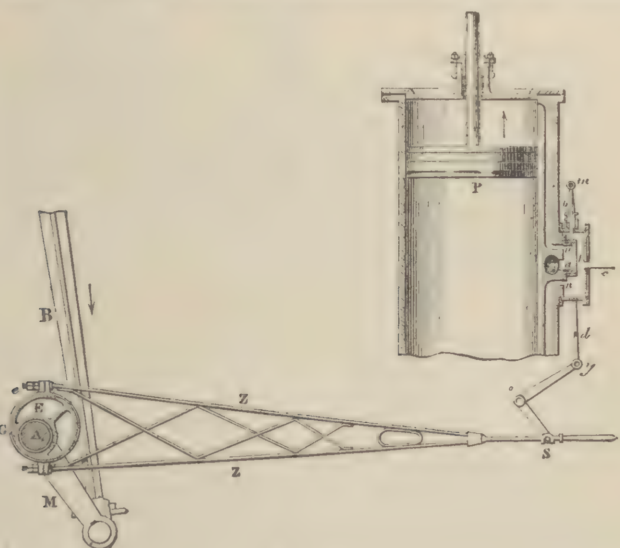


Fig. 321.

steam. The steam from the boiler passes by a pipe, *c*, into a cast-iron box on the side of the cylinder. In the sides of the cylinder there are three openings or *ports*, *u*, *n*, and *a*, of which *u* communicates by an internal conduit with the upper part of the cylinder, and *n* with the lower part. A slide, *t*, works over these three orifices. It is fixed to a

vertical rod, *b*, which is jointed at *m*, to a larger rod, *d*, and receives an upward and downward motion from the bent lever *yo*S, attached to the eccentric rod. When the slide is at the top of its course, as shown in the figure, the steam passes through *n* into the lower part of the cylinder, while the steam cannot pass through the orifice *u*, for it is covered by the slide.

But the vapour which is above the piston passes through *u* and through *a* into the hole *r*, from which it enters the condenser. The piston is then only pressed upwards, and therefore ascends.

When the slide is at the bottom of its course, the steam enters the cylinder by the aperture *u*, and passes from the lower part of the cylinder into the condenser by *n* and *a*. The piston consequently descends, and this motion goes on for each displacement of the slide.

The upward and downward motion of the slide is effected by means of the *eccentric*. This is a circular piece, E, fixed to the horizontal shaft A, but in such a manner that its centre does not coincide with the axis of this shaft. The eccentric works with gentle friction in a collar, C, to which the rod ZZ is fixed. The collar, without rotating, follows the motion of the eccentric, and receives an alternating motion in a horizontal direction, which it communicates to the lever S*oy*, and from thence to the slide.

427. **Single acting engine.**—In a *single acting engine* the steam only acts on the upper face of the piston ; a counterpoise fixed to the other end of the beam makes the piston rise. These engines were first constructed by Watt for pumping water from mines, and are still used for this purpose in Cornwall, and also for the supply of water to towns. They are preferred for these purposes from their simplicity, but for other uses they have been superseded by the double action engine.

Fig. 322 represents a section. The beam BB is of wood, with wooden segments at each end, to which chains are attached. One of these chains is connected with the piston, and the other with the pump. On the right of the cylinder A is a valve chest, C, into which steam passes from the boiler by the tube T. There are three valves, *m*, *n*, and *o*, on a vertical rod. The valves *m* and *o* open upwards, the valve *n* downwards.

When *m* and *o* are open, as shown in the drawing, the steam passes through the tube T, over the piston, while the steam, which is below, is forced into the condenser through the tube M. The piston therefore descends. The rod, on which are the valves *m*, *n*, and *o*, is connected with a bent lever, *dck*, moving on a joint *c*. This bent lever closes and opens the valves. For this purpose there are two catches, *b* and *a*, on a rod, F, connected with the beam, by means of which the rod works against the end of the bent lever. From the arrangement of the valves, as represented in the drawing, the piston sinks and carries with it the rod F, and, consequently, the catch strikes against the lever, and makes it sink at the same time as the rod *dmo* ; the valves *m* and *o* then close, while *n* opens.

The communication with the boiler as well as with the condenser is

now cut off, and the steam which has made the piston sink passes below by the pipe C. As it presses equally on both faces, the piston would remain at rest, but it rises in consequence of the traction of the weight Q. Very little force is necessary for this; for the pump, the rod of which

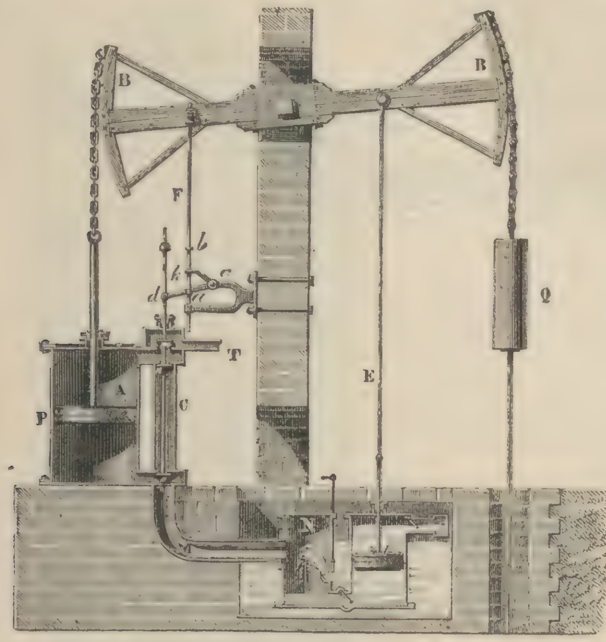


Fig. 322.

is fixed to the weight Q, only requires power when its piston rises. When the piston P is at the top of its course, the catch *a* strikes in turn against the lever *k*, raises the rod *dmo*, the steam again passes to the top of the piston, which again descends, and so on.

428. **Locomotives.**—*Locomotive engines*, or simply *locomotives*, are steam engines which, mounted on a carriage, propel themselves by transmitting their motion to wheels.

The parallel motion, the beam, and the fly wheel form no part of a locomotive. The principal parts are the *framework*, the *fire box*, the *casing* of the boiler, the *smoke box*, the *steam cylinders* with their valves, the *driving wheels*, and the *feed pump*.

The framework is of oak, and rests on the axles of the wheels. Fig. 323 represents the driver of the locomotive in the act of opening the regulator valve I, placed in the upper part of the *steam dome*. In the lower part of this is the fire box, from whence the flame and the products of combustion pass into the smoke box Y, and then into the

chimney Q, after having previously traversed 125 brass *fire tubes* which pass through the boiler. The boiler, which connects the fire box with the smoke box, is made of iron, and is cylindrical. It is cased with

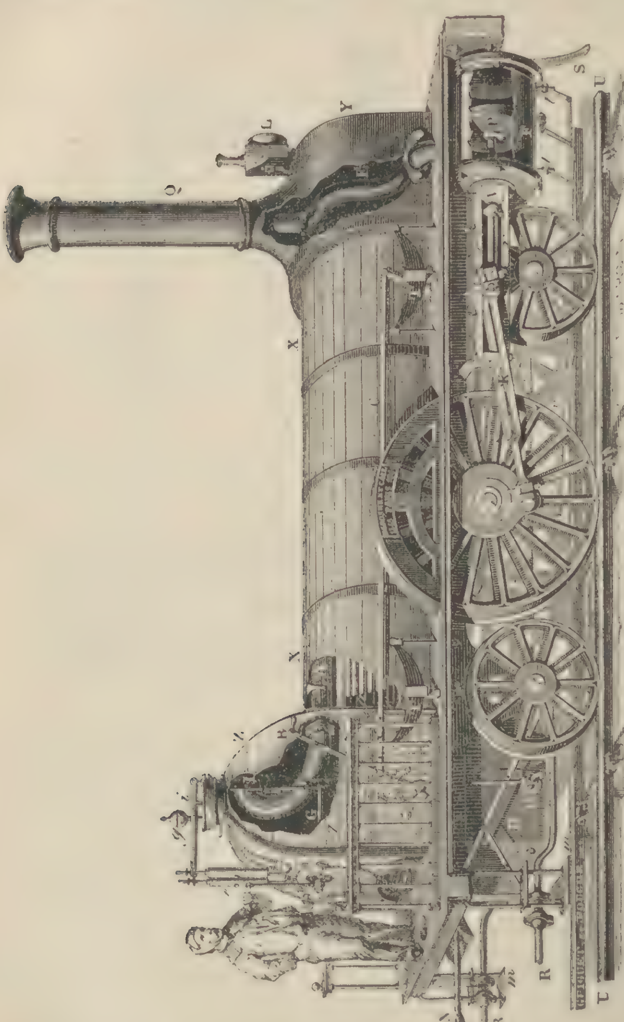


Fig. 323.

staves of mahogany, which, being a bad conductor, prevents its cooling too rapidly. The steam passes from the boiler into two cylinders placed on either side of the smoke box. There, by means of a steam chest

similar to that already described, it acts alternately on the two faces of the piston, the motion of which is transmitted to the axle of the large driving wheels. This arrangement of the slide valve is not seen in the drawing, because it is placed under the frame between the two cylinders. After having acted on the pistons, the steam is forced through the blast pipe E into the chimney, thus increasing the draught.

The motion of the pistons is transmitted to the two large driving wheels by two connecting rods, which, by means of cranks, connect the piston rods with the axles of the wheels. The alternating motion of the slide valve is effected by means of eccentrics placed on the axles of the large wheels.

The feeding or supply of water to the boiler is obtained by means of two pumps placed under the frame, and moved by eccentrics. These pumps suck the water from a reservoir placed on the *tender*, which is a carriage attached to the locomotive for carrying the necessary water and coal.

Explanation of figure 323.

A. Copper tube, into which steam passes by the extremity I, and which, dividing at the other end into two branches, conveys the steam to the two cylinders which contain the pistons.

B. Handle of the lever, by which the motion is reversed. It imparts motion to a rod, C, which communicates with the steam chest.

C. Rod by which the motion is reversed.

D. Lower part of the fire box and ash pan.

E. Escape pipe for the steam after acting on the pistons.

F. Iron cylinder containing a piston, P. There is one of these on each side of the engine, and the one in front is represented as being left open in order that the piston may be seen.

G. Rod which opens the regulator valve I, in order to allow the steam to pass into the tube A. In the drawing the driver holds in his hand the lever which moves this rod.

H. Cock for blowing off water from the boiler.

I. Regulator valve, which is opened and closed by hand, so as to regulate the quantity of steam passing into the cylinders.

K. Large rod connecting the head of the piston rod with the crank M of the driving wheel.

L. Lamp for use by night.

M. Crank, which transmits the motion of the piston to the axle of the large wheel.

N. Coupling iron, by which the tender is attached.

O. Fire door, by which coke is introduced.

P. Metallic piston, the rod of which is connected with the rod K.

Q. Chimney, by which both steam and smoke escape.

R, R. Feed pipes, through which the water in the tender passes to two force pumps, which are not shown in the drawing.

S. Guard for removing obstructions on the rails.

T, T. Springs on which the engine rests.

U, U. Iron rails fixed in chairs on wooden sleepers.

V. Frame of the stuffing box of the cylinder.

X, X. Cylindrical boiler, covered with mahogany staves, which, from their bad conductivity, hinder the loss of heat. The level of the water is just below the tube A. In the water are the tubes *aa*, through which the smoke and flames pass into the smoke box.

Y. Smoke box, in which the fire tubes *a* terminate.

Z, Z. Fire box, covered by a dome, into which the steam passes.

a. Brass tubes, of which there are 125, open at both ends, and terminating at one end in the fire box, and at the other in the smoke box. These tubes transmit to the water the heat of the fire.

bb. Toothed segment, placed on the side of the fire box, and in which the arm of the lever B works. When the handle is pushed forward or pulled back as far as it can go, the engine is in full forward or backward gear respectively; the intermediate teeth give various rates of expansion in backward and forward motion, the middle tooth being a dead point.

e. Cases containing springs by which the safety valves *i* are regulated.

g. Signal whistle.

i. Safety valves.

m, *m*. Steps.

n. Glass tube, showing the height of water in the boiler.

r, *r*. Guiding rods, for keeping the motion of the pistons in a straight line.

t, *t*. Blowing-off taps, for use when the pistons are in motion.

v. Rod by which motion is transmitted to these taps.

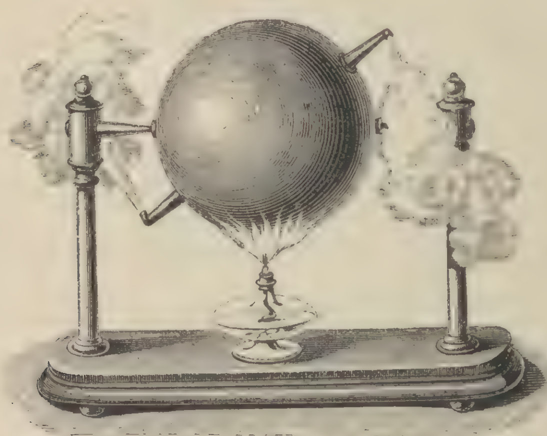


Fig. 324.

429. **Reaction machines. Eolipyle.**—In *reaction machines* steam acts by a reactive force like water in a hydraulic tourniquet (201). The idea of these machines is by no means new; Hero of Alexandria, who

invented the fountain which bears his name, described the following apparatus, which is known as the reaction machine.

It consists of a hollow metallic sphere which rotates on two pivots (fig. 324). At the ends of a diameter are two tubulures, pierced laterally in opposite directions by orifices through which vapour escapes. Water is introduced into this apparatus by heating it, and then allowing it to cool in cold water. If the apparatus be then heated to boiling, the vapour disengaged imparts to it a rotatory motion, which is due to the pressure of the vapour on the side opposite to that from which it escapes.

Numerous attempts have been made to use this reactive force of the vapour on a large scale as a motive force, and endeavours have also been made to cause steam to act by impulse by directing a jet of steam on the float board of a paddle wheel; but in both cases the steam exerts by no means so great an effect as is obtained when it acts by expansion on a piston.

430. **Various kinds of steam engines.**—A *low pressure engine* is one in which the tension of the vapour does not much exceed an atmosphere: and a *high pressure engine* is one in which the pressure of the steam usually exceeds this amount considerably. Low pressure engines are mostly *condensing engines*; in other words, they generally have a condenser where the steam becomes condensed after having acted on the piston: on the other hand, *high pressure engines* are frequently without a condenser; the locomotive is an example.

If the communication between the cylinder and boiler remains open during the whole motion of the piston, the steam retains essentially the same elastic force, and is said to act *without expansion*: but if, by a suitable arrangement of the slide valve, the steam ceases to pass into the cylinder when the piston is at $\frac{2}{3}$ or $\frac{3}{4}$ of its course, then the vapour *expands*; that is to say, in virtue of its elastic force, which is due to the high temperature, it still acts on the piston and causes it to finish its course. Hence a distinction is made between *expanding* and *non-expanding* engines.

431. **Work of an engine. Horse-power.**—The work of an engine is measured by the mean pressure on the piston × area of the piston × length of the stroke. In England the unit of work is the *foot-pound*; that is, the work performed in raising a weight of one pound through a height of a foot. Thus, to raise a weight of 14 pounds through a height of 20 feet would require 280 foot-pounds. In France the *kilogrammeter* is used; that is, the work performed in raising a kilogramme through a metre. This unit corresponds to 7·233 foot-pounds.

The *rate of work* in machines is the amount of work performed in a given time; a second or an hour, for example. In England the rates of work are compared by means of *horse-power*, which is a conventional unit, and represents 550 foot-pounds in a second. In France a similar unit is used, called the *cheval vapeur*, which represents the work performed in raising 75 kilogrammes through one metre in a second. It is equal to about 542 foot-pounds per second.

CHAPTER XI.

SOURCES OF HEAT AND COLD.

432. **Different sources of heat.**—The following different sources of heat may be distinguished : i. the *mechanical sources*, comprising friction, percussion, and pressure ; ii. the *physical sources*—that is, solar radiation, terrestrial heat, the molecular actions, the changes of condition, and electricity ; iii. the *chemical sources*, or molecular combinations, and more especially combustion.

In what follows, it will be seen that heat may be produced by reversing its effects ; as, for instance, when a liquid is solidified or a gas compressed (434) ; though it does not necessarily follow that the reversal of its effects in all cases causes heat to be produced—instead of it an equivalent of some other form of energy may be generated.

In like manner heat may be caused to disappear, or cold be produced, when a change such as heat can produce is brought about by other means, as when a liquid is vaporised or a solid liquefied by solution ; though here also the disappearance of heat is not always a necessary consequence of the production by other means of changes such as might be effected by heat.

MECHANICAL SOURCES.

433. **Heat due to friction.**—The friction of two bodies, one against the other, produces heat, which is greater the greater the pressure and the more rapid the motion. For example, the axles of carriage wheels, by their friction against the boxes, often become so strongly heated as to take fire. By rubbing together two pieces of ice in a vacuum below zero, Sir H. Davy partially melted them. In boring a brass cannon Rumford found that the heat developed in the course of 2½ hours was sufficient to raise 26½ pounds of water from zero to 100°, which represents 2650 thermal units (406). At the Paris Exhibition, in 1855, MM. Beaumont and Mayer exhibited an apparatus, which consisted of a wooden cone covered with hemp, and moving with a velocity of 400 revolutions in a minute, in a hollow copper cone, which was fixed and immersed in the water of an hermetically-closed boiler. The surfaces were kept covered with oil. By means of this apparatus 88 gallons of water were raised from 10 to 130 degrees in the course of a few hours.

In the case of flint and steel, the friction of the flint against the steel raises the temperature of the metallic particles, which fly off heated to such an extent that they take fire in the air.

Dr. Tyndall has devised an experiment by which the great heat developed by friction is illustrated in a striking manner. A brass tube (fig. 325), about 4 inches in length and ¾ of an inch in diameter, is fixed on a small wheel. By means of a cord passing round a much larger one this tube can be rotated with any desired velocity. The tube is three parts full of water, and is closed by a cork. In making the experiment the tube is pressed between a wooden clamp, while the wheel is rotated with some rapidity. The water rapidly becomes heated by the friction,

and its temperature soon exceeding the boiling point, the cork is projected to a height of several yards by the elastic force of the steam.

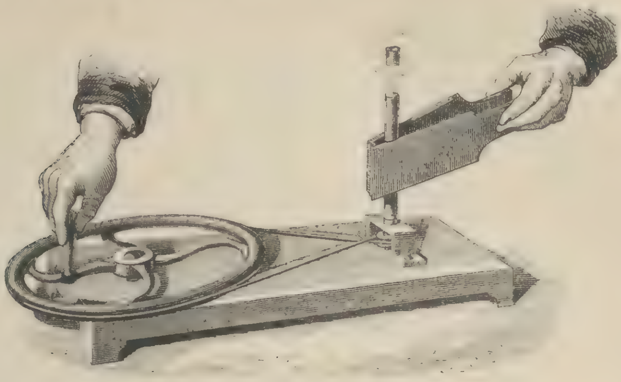


Fig. 325.

434. **Heat due to pressure and percussion.**—If a body be so compressed that its density is increased, its temperature rises according as the volume diminishes. Joule has verified this in the case of water and of oil, which were exposed to pressures of 15 to 25 atmospheres. In the case of water at 1·2° C., increase of pressure caused lowering of temperature, a result which agrees with the fact that water contracts by heat at this temperature. Similarly when weights are laid on metallic pillars, heat is evolved, and absorbed when they are removed. So in like manner the stretching of a metallic wire is attended with a diminution of temperature.

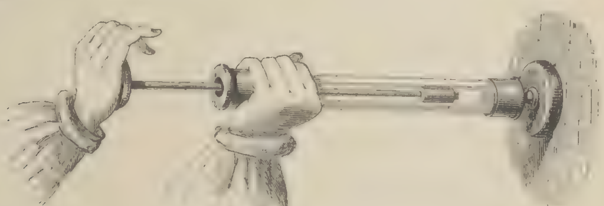


Fig. 326.

The production of heat by the compression of gases is easily shown by means of the *pneumatic syringe* (fig. 326). This consists of a glass tube with thick sides, closed hermetically by a leather piston. At the bottom of this, there is a cavity in which a small piece of tinder is placed. The tube being full of air, the piston is suddenly plunged downwards; the air thus compressed disengages so much heat as to ignite the tinder, which is seen to burn when the piston is rapidly withdrawn. The inflammation of the tinder in this experiment indicates a temperature of at

least 300°. At the moment of compression a bright flash is observed, which was originally attributed to the high temperature of the air; but it is simply due to the combustion of the oil which greases the piston. Instead of the tinder, cotton very slightly moistened with ether or bisulphide of carbon may be used.

The elevation of temperature produced by the pressure in the above experiment is sufficient to effect the combination, and therefore the detonation, of a mixture of hydrogen and oxygen.

Percussion is also a source of heat. In firing shot at an iron target, a sheet of flame is frequently seen at the moment of impact; and Mr. Whitworth has used iron shells which are exploded by the concussion on striking an iron target. A small piece of iron hammered on the anvil becomes very hot. The heat is not simply due to an approximation of the molecules, that is, to an increase in density, but arises from a vibratory motion imparted to them; for lead, which does not increase in density by percussion, nevertheless becomes heated.

The heat due to the impact of bodies is not difficult to calculate. Whenever a body moving with a velocity v is suddenly arrested in its motion, by whatever cause, its *vis viva* is converted into heat. This holds equally whatever be the cause to which the motion is due; whether it be that acquired by a stone falling from a height; by a bullet fired from a gun, or the rotation of a copper disc by means of a turning table. The *vis viva* of any moving body, as we have seen (56), is expressed by $\frac{mv^2}{2}$ or in foot-pounds by $\frac{wv^2}{2g}$, where w is the weight in pounds, v the velocity in feet per second, and g is about 32; and if the whole of this be converted into heat its equivalent in thermal units will be $\frac{wv^2}{2g \times 1390}$. Suppose, for instance, a lead ball weighing a pound be fired from a gun, and strike against a target, what amount of heat will it produce? We may assume that its velocity will be about 1,600 per second, then its *vis viva* will be $\frac{1 \times 1600^2}{2 \times 32} = 40{,}000$ foot-pounds, the equivalent of which in heat is $\frac{40000}{1390} = 28{\cdot}7$ thermal units. If we assume that the heat is equally distributed between the ball and the target then the share of the former will be 14·3 thermal units; and if, for simplicity's sake, we assume that its temperature is originally zero, then taking its specific heat at 0·0314 we shall have

$$1 \times 0{\cdot}0314 \times t = 14{\cdot}3 \text{ or } t = 457.^{\circ}$$

which is a temperature considerably above that of the melting point of lead (306).

By similar methods Mayer has calculated that if the motion of the earth were suddenly arrested the temperature produced would be sufficient to melt and even volatilise it; while if it fell into the sun as much heat would be produced as results from the combustion of 5000 spheres of carbon the size of our globe.

PHYSICAL SOURCES.

435. **Solar radiation.**—The most intense of all sources of heat is the sun. The cause of its heat is unknown; some have considered it to be an ignited mass experiencing immense eruptions, while others have regarded it as composed of layers acting chemically on each other like the couples of a voltaic battery, and giving rise to electrical currents, which produce light and solar heat. On both hypotheses the incandescence of the sun would have a limit.

Different attempts have been made to determine the quantity of heat annually emitted by the sun. M. Pouillet, by means of an apparatus which he calls a *pyrheliometer*, has calculated that if the total quantity of heat which the earth receives from the sun in the course of a year were employed to melt ice, it would be capable of melting a layer of ice all round the earth of 35 yards in thickness. But from the surface which the earth exposes to the solar radiation, and from the distance which separates the earth from the sun, the quantity of heat which the earth receives can only be $\frac{1}{2,381,000,000}$ of the heat emitted by the sun.

Faraday has calculated that the average amount of heat radiated in a day on each acre of ground in the latitude of London is equal to that which would be produced by the combustion of sixty sacks of coal.

Various hypotheses have been propounded to account for the invariability in the amount of heat emitted by the sun. The most probable supposition is that originally put forth by Mayer, but which has been developed by Waterston and Sir W. Thomson, according to which the heat which the sun loses by radiation is replaced by the fall of *meteoric stones* or *aerolites* against its surface. These are what we know as shooting stars, which often appear in the heavens with great brilliancy especially on the 14th August and 15th November. These fall against the sun with a velocity far transcending anything met with on the surface of our globe, and by their impact develope an amount of heat which more than compensates what the sun loses by radiation. It has been calculated that an amount falling into the sun every year which would not increase its thickness by more than 21 yards would be sufficient for this purpose.

436. **Terrestrial heat.**—Our globe possesses a heat peculiar to it, which is called the *terrestrial heat*. The variations of temperature which occur at the surface gradually penetrate to a certain depth, at which their influence becomes too slight to be sensible. It is hence concluded that the solar heat does not penetrate below a certain internal layer, which is called the *layer of constant temperature*: its depth below the earth's external surface varies, of course, in different parts of the globe; at Paris it is about 30 yards, and the temperature is constant at 11·8° C.

Below the layer of constant temperature, the temperature is observed to increase, on the average 1° C. for every 90 feet. This increase has been verified in mines and artesian wells. According to this, at a depth of 3,000 yards, the temperature of a corresponding layer would be 100°, and at a depth of 20 to 30 miles there would be a temperature sufficient

to melt all substances which exist on the surface. Hot springs and volcanoes confirm the existence of this central heat.

Various hypotheses have been proposed to account for the existence of this central heat. That most usually admitted by physicists is that the earth was originally in a liquid state in consequence of the high temperature, and that by radiation the surface has gradually solidified, so as to form a solid crust. The thickness of this crust is not believed to be more than 40 to 50 miles, and the interior is probably still in a liquid state. The cooling must be very slow, in consequence of the imperfect conductivity of the crust. For the same reason the central heat does not appear to raise the temperature of the surface more than $\frac{1}{36}$ of a degree.

437. **Heat produced by absorption and imbibition.**—Molecular phenomena, such as imbibition, absorption, capillary actions, are usually accompanied by disengagement of heat. Pouillet found that whenever a liquid is poured on a finely-divided solid, an increase of temperature is produced which varies with the nature of the substances. With inorganic substances, such as metals, the oxides, the earths, the increase is $\frac{4}{10}$ of a degree; but with organic substances, such as sponge, flour, starch, roots, dried membranes, the increase varies from 1 to 10 degrees.

The absorption of gases by solid bodies presents the same phenomena. Döbereiner found that when platinum, in the fine state of division known as platinum black, is placed in oxygen, it absorbs many hundred times its volume, and that the gas is then in such a state of density, and the temperature so high, as to give rise to intense combustions. Spongy platinum produces the same effect. A jet of hydrogen directed on it takes fire.

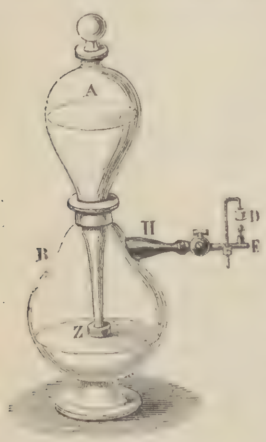


Fig. 327.

The apparatus known as *Döbereiner's Lamp* depends on this property of finely-divided platinum. It consists of two glass vessels (fig. 327). The first, A, fits in the lower vessel by means of a tubulure which closes it hermetically. At the extremity of the tubulure there is a mass of zinc, Z, immersed in dilute sulphuric acid. By the chemical action of the zinc on the dilute acid hydrogen gas is generated, which, finding no issue, forces the liquid out of the vessel B into the vessel A, so that the zinc is not in contact with the liquid. The stopper of the upper vessel is raised to give exit to the air in proportion as the water rises. On a copper tube, H, fixed in the side of the vessel B, there is a small cone, E, perforated by an orifice; above this there is some spongy platinum in the capsule D.

As soon now as the cock, which closes the tube H, is opened, the hydrogen escapes, and coming in contact with the spongy platinum, is ignited.

M. Favre, who has recently examined the question of the heat disengaged when a gas is absorbed by charcoal has found that the amount of heat produced by the absorption of a given weight of sulphurous acid, or of protoxide of nitrogen, greatly exceeds that which is disengaged in the liquefaction of the same weight of gas ; for carbonic acid, the heat produced by absorption exceeds even the heat which would be disengaged by the solidification of the gas. The heat produced by the absorption of these gases, cannot, therefore, be explained by assuming that the gas is liquefied, or even solidified in the pores of the charcoal. It is probable that it is due to that produced by the liquefaction of the gas, and the heat due to the imbibition of the liquid so produced in the charcoal.

The heat produced by the changes of condition has been already treated of in the articles *solidification* and *liquefaction* ; the heat produced by electrical action will be discussed under the head of *Electricity.*

CHEMICAL SOURCES.

438. **Chemical combinations. Combustion.**—Chemical combinations are usually accompanied by a certain elevation of temperature. When these combinations take place slowly, as when iron oxidises in the air, the heat produced is imperceptible ; but if they take place rapidly, the disengagement of heat is very intense. The same quantity of heat is produced in both cases, but when evolved slowly it is dissipated as fast as formed.

Combustion is chemical combination attended with the evolution of light and heat. In the ordinary combustion in lamps, fires, candles, the carbon and hydrogen of the coal, or of the oil, etc., combine with the oxygen of the air. But combustion does not necessarily involve the presence of oxygen. If either powdered antimony or a fragment of phosphorus be placed in a vessel of chlorine, it unites with chlorine, producing thereby heat and flame.

Many combustibles burn with flame. A *flame* is a gas or vapour raised to a high temperature by combustion. Its illuminating power varies with the nature of the product formed. The presence of a solid body in the flame increases the illuminating power. The flames of hydrogen, carbonic oxide, and alcohol are pale, because they only contain gaseous products of combustion. But the flames of candles, lamps, coal gas, have a high illuminating power. They owe this to the fact that the high temperature produced decomposes certain of the gases with the production of carbon, which, not being perfectly burned, becomes incandescent in the flame. Coal gas, when burnt in an arrangement by which it obtains an adequate supply of air, is almost entirely devoid of luminosity. A non-luminous flame may be made luminous by placing in it platinum wire, or asbestos. The temperature of a flame does not depend on its illuminating power. A hydrogen flame, which is the palest of all flames, gives the greatest heat.

439. **Heat disengaged during combustion.**—Many physicists, more especially Lavoisier, Rumford, Dulong, Despretz, Hess, Favre and Silber-

mann, and Andrews, have investigated the quantity of heat disengaged by various bodies in chemical combinations.

In these experiments Lavoisier used the ice calorimeter already described. Rumford used a calorimeter known by his name, which consists of a rectangular copper canister filled with water. In this canister there is a worm which passes through the bottom of the box, and terminates below in an inverted funnel. Under this funnel is burnt the substance experimented upon. The products of combustion, in passing through the worm, heat the water of the canister, and from the increase of its temperature the quantity of heat evolved is calculated. MM. Despretz and Dulong have successively modified Rumford's calorimeter by allowing the combustion to take place, not outside the canister, but in a chamber placed in the liquid itself; the oxygen necessary for the combustion entered by a tube in the lower part of the chamber, and the products of combustion escaped by another tube placed at the upper part and twisted in a serpentine form in the mass of the liquid to be heated. MM. Favre and Silbermann have improved this calorimeter very greatly (421), not only by avoiding or taking account of all possible sources of error, but by arranging it for the determination of the heat evolved in other chemical actions than those of ordinary combustion.

The experiments of MM. Favre and Silbermann are the most trustworthy, as having been executed with the greatest care. They agree very closely with those of Dulong. Taking as thermal unit the heat necessary to raise the temperature of a pound of water through *one* degree Centigrade, the following table gives the thermal units in round numbers disengaged by a pound of each of the substances in burning in oxygen:—

Hydrogen	34462	Sulphur	2220
Marsh gas	13063	Anthracite	8460
Olefiant gas	11858	Charcoal	8080
Oil of turpentine	10852	Coal	8000
Olive oil	9860	Tallow	8000
Ether	9030	Diamond	7770
Coke	7000	Absolute alcohol	7180
Wood, dry	4025	Phosphorus	5750
Wood, moist	3100	Bisulphide of carbon	3401
Carbonic oxide	2400	Iron	1576

The experiments of Dulong, of Despretz, and of Hess prove that a body in burning always produces the same quantity of heat in reaching the same degree of oxidation, whether it attains this at once or only reaches it after passing through intermediate stages. Thus a given weight of carbon gives out the same amount of heat in burning directly to carbonic acid as if it were first changed into carbonic oxide, and then this burnt into carbonic acid.

HEATING.

440. **Different kinds of heating.**—*Heating* is the art of utilising for domestic and industrial purposes the sources of heat which nature offers to us.

Our principal source of artificial heat is the combustion of coal, coke, turf, wood, and charcoal.

We may distinguish five kinds of heating, according to the apparatus used: 1st, heating with an open fire; 2nd, heating with an enclosed fire, as with a stove; 3rd, heating by hot air; 4th, heating by steam; 5th, heating by the circulation of hot water.

441. **Fire-places.**—Fire-places are open hearths built against a wall under a chimney, through which the products of combustion escape.

However much they may be improved, fire-places will always remain the most imperfect and costly mode of heating, for they only render available 13 per cent. of the total heat yielded by coal or coke, and 6 per cent. of that by wood. This enormous loss of temperature arises from the fact, that the current of air necessary for combustion always carries with it a large quantity of the heat produced, which is lost in the atmosphere. Hence it was that Franklin said fire-places should be adopted in cases where the smallest quantity of heat was to be obtained from a given quantity of combustible. Notwithstanding their want of economy, however, they will always be preferred as the healthiest and pleasantest mode of heating, on account of the cheerful light which they emit, and the ventilation which they ensure.

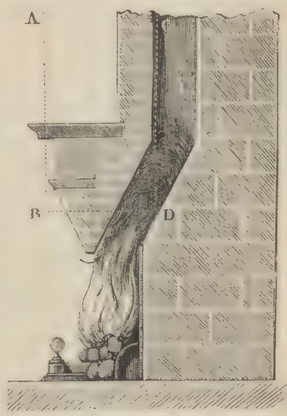


Fig. 328.

442. **Draught of fire-places.**—The *draught* of a fire is the upward current in the chimney caused by the ascent of the products of combustion; when the current is rapid and continuous, the chimney is said to *draw* well.

The draught is caused by the difference between the temperature of the inside and that on the outside of the chimney; for, in consequence of this difference, the gaseous substances which fill the chimney are lighter than the air of the room, and consequently equilibrium is impossible. The weight of the column of gas CD, fig. 328, in the chimney being less than that of the external column of air AB of the same height, there is a pressure from the outside to the inside which causes the products of combustion to ascend the more rapidly in proportion as the difference in weight of the two gaseous masses is greater.

The velocity of the draught of a chimney may be determined theoretically by the formula

$$v = \sqrt{2g\alpha(t' - t)h},$$

in which g is the acceleration of gravity, α the coefficient of the expansion of air, h the height of the chimney, t' the mean temperature of the air inside the chimney, and t the temperature of the surrounding air.

The currents caused by the difference in temperature of two communicating gaseous masses may be demonstrated by placing a candle near the

top and near the bottom of the partially-opened door of a warm room. At the top, the flame will be turned from the room towards the outside, while the contrary effect will be produced when the candle is placed on the ground. These two effects are caused by the current of heated air which issues by the top of the door, while the cold air which replaces it enters at the bottom.

In order to have a good draught a chimney ought to satisfy the following conditions:

i. The section of the chimney ought not to be larger than is necessary to allow an exit for the products of combustion, otherwise ascending and descending currents are produced in the chimney, which cause it to smoke. It is advantageous to place on the top of the chimney a conical pot narrower than the chimney, so that the smoke may escape with sufficient velocity to resist the action of the wind.

ii. The chimney ought to be sufficiently high, for, as the draught is caused by the excess of the external over the internal pressure, this excess is greater in proportion as the column of heated air is longer.

iii. The external air ought to pass into the chamber with sufficient rapidity to supply the wants of the fire. In a hermetically-closed room the combustibles would not burn, or descending currents would be formed which would drive the smoke into the room. Usually air enters in sufficient quantity by the crevices of the doors and windows.

iv. Two chimneys should not communicate, for if one draws better than the other, a descending current of air is produced in the latter, which carries smoke with it.

443. **Stoves.**—*Stoves* are apparatus for heating with a detached fire, placed in the room to be heated, so that the heat radiates in all directions round the stove. At the lower part is the draught hole by which the air necessary for combustion enters. The products of combustion escape by means of iron chimney pipes. This mode of heating is one of the most economical, but it is by no means so healthy as that by open fire-places, for the ventilation is very bad, more especially where, as in Sweden, the stoves are fed from the outside of the room. These stoves also emit a bad smell, probably arising from the decomposition of organic substances in the air by their contact with the heated sides of the chimney pipes; or possibly, as Deville and Troost's recent researches seem to show, from the diffusion of gases through the heated sides of the stove.

The heating is very rapid with blackened metal stoves, but they also cool very rapidly. Stoves constructed of polished earthenware, which are common on the Continent, heat more slowly, but more pleasantly, and they retain the heat longer.

444. **Heating by steam.**—Steam, in condensing, gives up its latent heat of vaporisation, and this property has been used in heating baths, workshops, public buildings, hothouses, &c. For this purpose steam is generated in boilers similar to those used for steam-engines, and is then made to circulate in pipes placed in the room to be heated. The vapour condenses, and in doing so imparts to the pipes the latent heat, which becomes free, and thus heats the surrounding air.

445. **Heating by hot air.**—Heating by hot air consists in heating the air in the lower part of a building, from whence it rises to the higher parts in virtue of its lessened density. The apparatus is arranged as represented in figure 329.

A series of bent tubes, AB, only one of which is shown in the figure, is placed in a furnace, F, in the cellar. The air passes into the tubes through the lower end A, where it becomes heated, and rising in the direction of the arrows, reaches the room M by the higher aperture B. The various

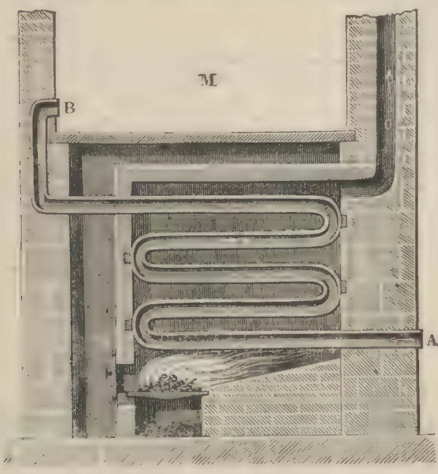


Fig. 329.

rooms to be heated are provided with one or more of those apertures which are placed as low in the room as possible. The conduit O is an ordinary chimney.

These apparatus are more economical than open fire-places, but they are less healthy, owing to the want of ventilation.

446. **Heating by hot water.**—This consists of a continuous circulation of water, which having been heated in a boiler, rises through a series of tubes, and then, after becoming cool, passes into the boiler again by a similar series.

Figure 330 represents an apparatus for heating a building of several stories. The heating apparatus, which is in the cellar, consists of a bell-shaped boiler, *oo*, with an internal flue, F. A long pipe, M, fits in the upper part of the boiler, and also in the reservoir Q, placed in the upper part of the building to be heated. At the top of this reservoir there is a safety valve, *s*, by which the pressure of the vapour in the interior can be regulated.

The boiler, the pipe M, and a portion of the reservoir, Q, being filled with water, as it becomes heated in the boiler an ascending current of hot water rises to the reservoir Q, while at the same time descending

currents of colder and denser water pass from the lower part of the reservoir Q into receivers, *b*, *d*, *f*, filled with water. The water from these passes again through pipes into other receivers, *a*, *c*, *e*, and ultimately reaches the lower part of the boiler.

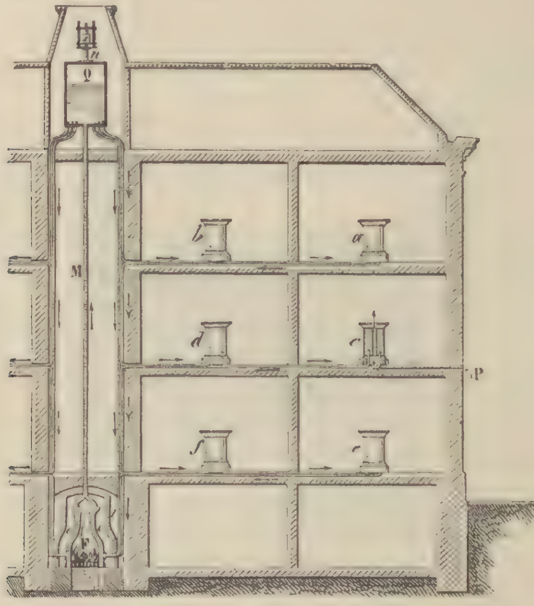


Fig. 330.

During this circulation the hot water heats the pipes and the receivers, which thus become true water stoves. The number and the dimensions of these parts are readily determined from the experimental fact that a cubic foot of water is sufficient to communicate the necessary heat to 3200 cubic feet of air. In the interior of the receivers *a*, *b*, *c*, *d*, *e*, *f* there are cast-iron tubes which communicate with the outside by pipes, P, placed underneath the flooring. The air becomes heated in these tubes, and emerges at the upper part of the receivers.

The principal advantage of this mode of heating is that of giving a temperature which is constant for a long time; for the mass of water only cools slowly. It is much used in hothouses, baths, artificial incubation, drying rooms, and generally wherever a uniform temperature is desired.

SOURCES OF COLD.

447. **Various sources of cold.**—Besides the cold caused by the passage of a body from the solid to the liquid state, of which we have already

spoken, cold is produced by the expansion of gases, by radiation in general, and more especially by nocturnal radiation.

448. **Cold produced by the expansion of gases.**—We have seen, that when a gas is compressed, the temperature rises. The reverse of this is also the case : when a gas is rarefied a reduction of temperature ensues, because a quantity of sensible heat disappears when the gas becomes increased to a larger volume. This may be shown by placing a delicate Breguet's thermometer under the receiver of an air-pump, and exhausting; at each stroke of the piston the needle moves in the direction of zero, and regains its original temperature when air is admitted. Kirk has invented a machine for the manufacture of ice, which depends on this property. The heat developed by the compression of air is removed by a current of cold water; the vessel containing the compressed air being placed in brine, the air is allowed to expand; in so doing it cools the brine so considerably as to freeze water contained in vessels placed in the brine. It is stated that by this means a ton of coals (used in working a steam-engine by which the compression is effected) can produce a ton of ice.

449. **Cold produced by nocturnal radiation.**—During the day, the ground receives from the sun more heat than radiates into space, and the temperature rises. The reverse is the case during night. The heat which the earth loses by radiation is no longer compensated for, and consequently a fall of temperature takes place, which is greater according as the sky is clearer, for clouds send towards the earth rays of greater intensity than those which come from the celestial spaces. In some winters it has been found that rivers have not frozen, the sky having been cloudy, although the thermometer has been for several days below $-4°$; while in other less severe winters the rivers freeze when the sky is clear. The emissive power exercises a great influence on the cold produced by radiation; the greater it is the greater is the cold.

In Bengal, the nocturnal cooling is used in manufacturing ice. Large flat vessels containing water are placed on non-conducting substances, such as straw or dry leaves. In consequence of the radiation the water freezes, even when the temperature of the air is 10° C. The same method can be applied in all cases with a clear sky.

It is said that the Peruvians, in order to preserve the shoots of young plants from freezing, light great fires in their neighbourhood, the smoke of which, producing an artificial cloud, hinders the cooling produced by radiation.

450. **Absolute zero of temperature.**—As a gas is increased $\frac{1}{273}$ of its volume for each degree Centigrade, it follows that at a temperature of 273° C. the volume of any gas measured at zero is doubled. In like manner, if the temperature of a given volume at zero were lowered through $-273°$, the contraction would be equal to the volume; that is, the volume would not exist.

At this temperature the motion of the molecules of the gas would completely cease, and the pressure thereby occasioned. In all probability, before reaching this temperature, gases would undergo some change.

This point on the Centigrade scale is called the *absolute zero of temperature*; the temperatures reckoned from this point are called *absolute temperatures*. They are clearly obtained by adding 273 to the temperature on the Centigrade scale.

CHAPTER XII.

MECHANICAL EQUIVALENT OF HEAT.

451. **Mechanical equivalent of heat.**—If the various instances of the production of heat by motion be examined, it will be found that in all cases mechanical force is consumed. Thus, in rubbing two bodies against each other, motion is apparently destroyed by friction; it is not, however, lost, but appears in the form of a motion of the particles of the body; the motion of the mass is transformed into a motion of the molecules.

Again, if a body be allowed to fall from a height, it strikes against the ground with a certain velocity. According to older views its motion is destroyed, *vis viva* is lost. This, however, is not the case; the *vis viva* of the body appears as *vis viva* of its molecules.

In the case, too, of chemical action, the most productive artificial source of heat, it is not difficult to conceive that there is in the act of combining an impact of the dissimilar molecules against each other, an effect analogous to the production of heat by the impact of masses of matter against each other.

In like manner, heat may be made to produce motion, as in the case of the steam-engine, the propulsion of shot from a gun.

Traces of a view that there is a connection between heat and motion are to be met with in the older writers, Bacon, for example; and Locke says: 'Heat is a very brisk agitation of the insensible parts of the object, which produces in us that sensation from whence we denominate the object hot; so that what in our sensation is heat, in the object is nothing but motion.' Rumford, in explaining his great experiment of the production of heat by friction, was unable to assign any other cause for the heat produced than motion; and Davy, in the explanation of his experiment of melting ice by friction in vacuo, expressed similar views. Carnot, in a work on the steam-engine, published in 1824, also indicated a connection between heat and work.

The views, however, which had been stated by isolated writers, had little or no influence on the progress of scientific investigation, and it is in the year 1842 that the modern theories may be said to have had their origin. In that year Dr. Mayer, a physician in Heilbronn, formally stated that there exists a connection between heat and work; and he it was who first introduced into science the expression '*mechanical equivalent of heat.*' Mayer also gave a method by which this equivalent could be calculated; the particular results, however, are of no value, as the method, though correct in principle, is founded on incorrect data.

In the same year, too, Colding of Copenhagen published experiments on the production of heat by friction, from which he concluded that the evolution of heat was proportional to the mechanical energy expended.

About the same time as Mayer, but quite independently of him, Joule commenced a series of experimental investigations on the relation between heat and work. These first drew the attention of scientific men to the subject, and were admitted as a proof that the transformation of heat into mechanical energy, or of mechanical energy into heat, always takes place in a definite numerical ratio.

Subsequently to Mayer and Joule, several physicists by their theoretical and experimental investigations have contributed to establish the mechanical theory of heat, namely, in this country, Sir W. Thomson and Rankine; in Germany, Helmholtz, Clausius, and Holtzmann; and in France Clapeyron and Regnault.

The following are some of the most important and satisfactory of Joule's experiments.

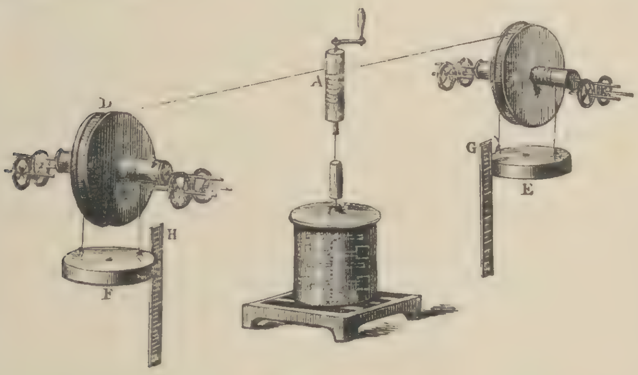


Fig. 331.

A copper vessel, B (fig. 331), was provided with a brass paddle-wheel (indicated by the dotted lines), which could be made to rotate about a vertical axis. Two weights, E and F, were attached to cords which passed over the pulleys C and D, and were connected with the axis A. These weights in falling caused the wheel to rotate. The height of the fall, which in Joule's experiments was about 63 feet, was indicated on the scales G and H. The roller A was so constructed that by detaching a pin the weights could be raised without moving the wheel. The vessel B was filled with water and placed on a stand, and the weights allowed to sink. When they had reached the ground, the roller was detached from the axis and the weights again raised, the same operations being repeated 20 times. The heat produced was measured by ordinary calorimetric methods.

The work expended is measured by the product of the weight into the height through which it falls, or wh, less the labour lost by the friction of

the apparatus. This is diminished as far as possible by the use of friction wheels, and its amount is determined by connecting C and D without causing them to pass over A, and then determining the weight necessary to communicate to them a uniform motion.

In this way it has been found that a thermal unit—that is, the quantity of heat by which a pound of water is raised through 1° C.—is generated by the expenditure of the same amount of work as would be required to raise 1392 pounds through 1 foot, or 1 pound through 1392 feet. This is expressed by saying that the mechanical equivalent of the thermal unit is 1392 foot-pounds.

The friction of an iron paddle-wheel in mercury gave 1397 foot-pounds, and that of the friction of two iron-plates gave 1395 foot-pounds, as the mechanical equivalent of one thermal unit.

In another series of experiments, the air in a receiver was compressed by means of a force pump, both being immersed in a known weight of water at a known temperature. After 300 strokes of the piston, the heat, C, was measured which the water had gained. This heat was due to the compression of the air and to the friction of the piston. To eliminate the latter influence, the experiment was made under the same conditions, but leaving the receiver open. The air was not compressed, and 300 strokes of the piston developed C' thermal units. Hence $C - C'$ is the heat produced by the compression of the gas. Representing the foot-pounds expended in producing this heat by W, we have $\frac{W}{C - C'}$ for the value of the mechanical equivalent E. By this method Joule obtained the number 1442.

The mean number which Joule adopted for the mechanical equivalent of one thermal unit on the Centigrade scale is 1390 foot-pounds; on the Fahrenheit scale it is 772 foot-pounds. This number is called *Joule's equivalent.*

The following is the method which Mayer employed in calculating the mechanical equivalent of heat. It is taken with slight modifications from Prof. Tyndall's work on 'Heat,' who, while strictly following Mayer's reasoning, has corrected his data.

Let us suppose that a rectangular vessel with a section of a square foot contains at 0° a cubic foot of air under the ordinary atmospheric pressure; and let us suppose that it is enclosed by a piston without weight.

Suppose now that the cubic foot of air is heated until its volume is doubled: from the coefficient of expansion of air we know that this is the case at 273° C. The gas in doubling its volume will have raised the piston through a foot in height; it will have lifted the atmospheric pressure through this distance. But the atmospheric pressure on a square foot is in round numbers $15 \times 144 = 2160$ pounds. Hence a cubic foot of air in doubling its volume has lifted a weight of 2160 pounds through a height of a foot.

Now a cubic foot of air at zero weighs 1·29 ounces, and the specific heat of air under constant pressure, that is, when it can expand freely, as

compared with that of an equal weight of water, is 0·24; so that the quantity of heat which will raise 1·29 ounces of air through 273° will only raise $0·24 \times 1·29 = 0·31$ oz. of water through the same temperature; but 0·31 oz. of water raised through 273° is equal to 5·29 pounds of water raised through 1° C.

That is, the quantity of heat which will double the volume of a cubic foot of air, and in so doing will lift 2160 pounds through a height of a foot, is 5·29 thermal units.

Now in the above case the gas has been heated under constant pressure, that is, when it could expand freely. If, however, it had been heated under constant volume, its specific heat would have been less in the ratio 1 : 1·414 (418), so that the quantity of heat required under these circumstances to raise the temperature of a cubic foot of air would be $5·29 \times \frac{1}{1·41} = 3·74$. Deducting this from 5·29, the difference 1·55 represents the weight of water which would have been raised 1° C. by the excess of heat imparted to the air when it could expand freely. But this excess has been consumed in the work of raising 2160 pounds through a foot. Dividing this by 1·55 we have 1393. Hence the heat which will raise a pound of water through 1° C. will raise a weight of 1393 pounds through a height of a foot; a numerical value of the mechanical equivalent of heat agreeing as closely as can be expected with that which Joule adopted as the most certain of his experimental results.

The law of the relation of heat to mechanical energy may thus be stated. *Heat and mechanical energy are mutually convertible; and heat requires for its production, and produces by its disappearance, mechanical energy in the ratio of* 1390 *foot-pounds for every thermal unit.*

A variety of experiments may in like manner be adduced to show that whenever heat disappears work is produced. For example, if in a reservoir immersed in water the air be compressed to the extent of 10 atmospheres: supposing that now, when the compressed air has acquired the temperature of the water, it be allowed to act upon a piston loaded by a weight, the weight is raised. At the same time the water becomes cooler, showing that a certain quantity of heat had disappeared in producing the mechanical effort of raising the weight.

This may also be illustrated by the following experiment, due to Prof. Tyndall.

A strong metal box is taken, provided with a stopcock, on which can be screwed a small condensing pump. Having compressed the air by its means, as it becomes heated by this process, the box is allowed to stand for some time, until it has acquired the temperature of the surrounding medium. On opening the stopcock, the air rushes out; it is expelled by the expansive force of the internal air; in short, the air drives itself out. Work is therefore performed by the gas, and there should be a disappearance of heat; and if the jet of gas be allowed to strike against the thermo-pile, the galvanometer is deflected, and the direction of its deflection indicates a cooling (fig. 332).

If, on the contrary, the experiment is made with an ordinary pair of

bellows, and the current of air is allowed to strike against the battery, the deflection of the galvanometer is in the opposite direction, indicating

Fig. 332.

an increase of temperature (fig. 333). In this case the hand of the experimenter performs the work, which is converted into heat.

Joule placed in a calorimeter two equal copper reservoirs, which could be connected by a tube. One of these contained air at 22 atmospheres,

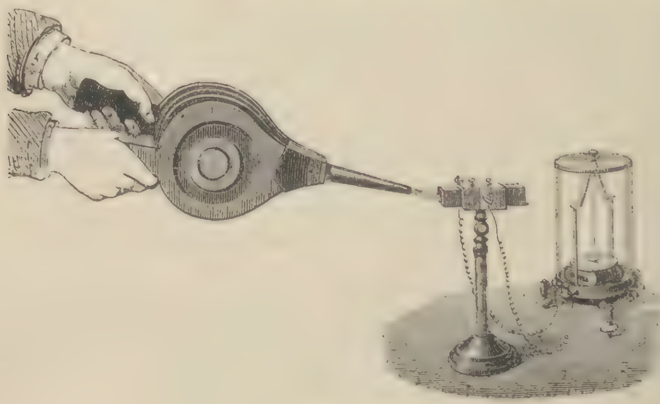


Fig. 333.

the other was exhausted. When they were connected, they came into equilibrium under a pressure of 11 atmospheres; but as the gas in expanding had done no work, there was no alteration in temperature. When, however, the second reservoir was full of water, the air in entering was

obliged to expel it and thus perform work, and the temperature sank, owing to an absorption of heat.

For further information the student of this subject is strongly recommended to read Professor Tyndall's *Heat as a Mode of Motion*, in which the phenomena of heat are throughout explained in accordance with modern views. A condensed, though complete and systematic, account of the dynamical theory of heat is met with in Professor Foster's articles on 'Heat,' in Watt's *Dictionary of Chemistry*.

BOOK VII.

ON LIGHT.

CHAPTER I.

TRANSMISSION, VELOCITY, AND INTENSITY OF LIGHT.

452. **Theories of light.**—*Light* is the agent which, by its action on the retina, excites in us the sensation of vision. That part of physics which deals with the properties of light is known as *optics*.

In order to explain the origin of light, various hypotheses have been made, the most important of which are the *emission* or *corpuscular* theory, and the *undulatory* theory.

On the *emission* theory it is assumed that luminous bodies emit, in all directions, an imponderable substance, which consists of molecules of an extreme degree of tenuity : these are propagated in right lines with an almost infinite velocity. Penetrating into the eye they act on the retina, and determine the sensation which constitutes vision.

On the undulatory theory, all bodies, as well as the celestial spaces, are filled by an extremely subtle elastic medium, which is called the *luminiferous ether*. The luminosity of a body is due to an infinitely rapid vibratory motion of its molecules, which, when communicated to the ether, is propagated in all directions in the form of spherical waves, and this vibratory motion, being thus transmitted to the retina, calls forth the sensation of vision. The vibrations of the ether take place not in the direction of the wave, but in a plane at right angles to it. The latter are called the *transversal* vibrations. An idea of these may be formed by shaking a rope at one end. The vibrations, or to and fro movements, of the particles of the rope, are at right angles to the length of the rope, but the onward motion of the wave's form is in the direction of the length of the rope.

On the emission theory the propagation of light is effected by a motion of *translation* of particles of light thrown out from the luminous body, as a bullet is discharged from a gun ; on the undulatory theory there is no progressive motion of the particles themselves, but only of the state of disturbance which was communicated by the luminous body ; it is a motion of *oscillation*, and, like the propagation of waves in water, takes place by a series of vibrations.

The luminiferous ether penetrates all bodies, but on account of its

extreme tenuity it is uninfluenced by gravitation; it occupies space, and although it presents no appreciable resistance to the motion of the denser bodies, it is possible that it hinders the motion of the smaller comets. It has been found, for example, that Encke's comet, whose period of revolution is about $3\frac{1}{3}$ years, has its period diminished by about 0·11 of a day at each successive rotation, and this diminution is ascribed by some to the resistance of the ether.

The fundamental principles of the undulatory theory were enunciated by Huyghens, and subsequently by Euler. The emission theory, principally owing to Newton's powerful support, was for long the prevalent scientific creed. The undulatory theory was adopted and advocated by Young, who showed how a large number of optical phenomena, particularly those of diffraction, were to be explained by that theory. Subsequently to, though independently of, Young, Fresnel showed that the phenomena of diffraction, and also those of polarisation, are explicable on the same theory, which, since his time, has been generally accepted.

The undulatory theory not only explains the phenomena of light, but it reveals an intimate connection between these phenomena and those of heat; it shows, also, how completely analogous the phenomena of light are to those of sound, regard being had to the differences of the media in which these two classes of phenomena take place.

453. **Luminous, transparent, translucent, and opaque bodies.**—*Luminous* bodies are those which emit light, such as the sun, and ignited bodies. *Transparent* or *diaphanous* bodies are those which readily transmit light, and through which objects can be distinguished; water, gases, polished glass, are of this kind. *Translucent* bodies transmit light, but objects cannot be distinguished through them; ground glass, oiled paper, etc., belong to this class. *Opaque* bodies do not transmit light; for example, wood, metals, etc. No bodies are quite opaque; they are all more or less translucent when cut in sufficiently thin leaves.

Foucault has recently shown that when the object glass of a telescope is thinly silvered, the layer is so transparent, that the sun can be viewed through it without danger to the eyes, since the metallic surface reflects the greater part of the heat and light.

454. **Luminous ray and pencil.**—A *luminous ray* is the line in which light is propagated; a *luminous pencil* is a collection of rays from the same source; it is said to be *parallel* when it is composed of parallel rays, *divergent* when the rays separate from each other, and *convergent*, when they tend towards the same point. Every luminous body emits divergent rectilinear rays from all its points, and in all directions.

455. **Propagation of light in a homogeneous medium.**—A *medium* is any space or substance which light can traverse, such as a vacuum, air, water, glass, etc. A medium is said to be homogeneous when its chemical composition and density are the same in all parts.

In every homogeneous medium light is propagated in a right line. For, if an opaque body is placed in the right line which joins the eye and the luminous body, the light is intercepted. The light which passes into a dark room by a small aperture, leaves a luminous trace, which is

visible from the light falling on the particles suspended in the atmosphere.

Light changes its direction on meeting an object which it cannot penetrate, or when it passes from one medium to another. These phenomena will be described under the heads *reflection* and *refraction*.

456. **Shadow, penumbra.**—When light falls upon an opaque body it cannot penetrate into the space immediately behind it, and this space is called the *shadow*.

In determining the extent and the shape of a shadow projected by a body, two cases are to be distinguished: that in which the luminous source is a single point, and that in which it is a body of any given extent.

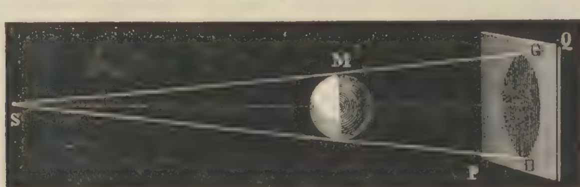


Fig. 334.

In the first case, let S (fig. 334) be the luminous point, and M a spherical body, which causes the shadow. If an infinitely long straight line, SG, move round the sphere M tangentially, always passing through the point S, this line will produce a conical surface, which, beyond the sphere, separates that portion of space which is in shadow from that which is illuminated. In the present case, on placing behind the opaque body a screen, PQ, the limit of the shadow HG will be sharply defined. This is not, however, usually the case, for luminous bodies have always a certain magnitude, and are not merely luminous points.

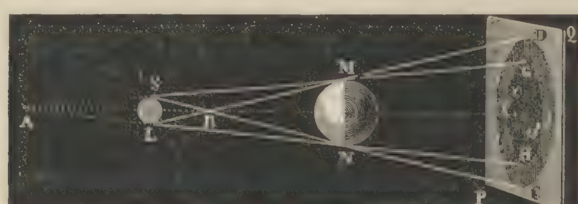


Fig. 335.

Suppose that the luminous and illuminated bodies are two spheres, SL and MN (fig. 335). If an infinite straight line, AG, moves tangentially to both spheres, always cutting the line of the centres in the point A, it will produce a conical surface with this point for a summit, and which traces behind the sphere MN a perfectly dark space, MGHN. If a second right line, LD, which cuts the line of centre in B, moves tangentially to the two spheres, so as to produce a new conical surface, BDC, it will be seen that

all the space outside this surface is illuminated, but that the part between the two conical surfaces is neither quite dark nor quite light. So that if a screen, PQ, is placed behind the opaque body, the portion *c*G*d* H of the screen is quite in the shadow, while the space *ab* receives light from certain parts of the luminous body, and not from others. It is brighter than the true shadow, and not so bright as the rest of the screen, and it is accordingly called the *penumbra*.

Shadows such as these are *geometrical shadows; physical shadows*, or those which are really seen, are by no means so sharply defined. A certain quantity of light passes into the shadow, even when the source of light is a mere point, and conversely the shadow influences the illuminated part. This phenomenon, which will be afterwards described, is known by the name of *diffraction*.

457. **Images produced by small apertures.**—When luminous rays, which pass into a dark chamber *through a small aperture*, are received upon a screen, they form images of external objects. These images are inverted; their shape is always that of the external objects, and is independent of the shape of the aperture.

The inversion of the images arises from the fact that the luminous rays proceeding from external objects, and penetrating into the chamber, cross one another in passing the aperture, as shown in fig. 336. Con-

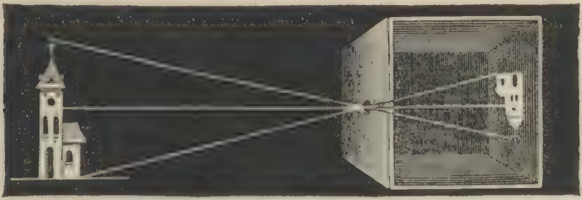


Fig. 336.

tinuing in a straight line, the rays from the higher parts meet the screen at the lower parts, and inversely, those which come from the lower parts meet the higher parts of the screen. Hence the inversion of the image. In the article *Camera obscura*, it will be seen how the brightness and precision of the images are increased by means of lenses.

In order to show that the shape of the image is independent of that of the aperture, when the latter is sufficiently small, and the screen at an adequate distance, imagine a triangular aperture, O (fig. 337), made in the door of a dark chamber, and let *ab* be a screen on which is received the image of a flame, AB. A divergent pencil from each point of the flame penetrates through the aperture, and forms on the screen a triangular image resembling the aperture. But the union of all these partial images produces a total image of the same form as the luminous object. For if we conceive that an infinite straight line moves round the aperture, with the condition that it is always tangential to the luminous object AB, and that the aperture is very small, the straight line describes two cones, the

apex of which is the aperture, while one of the bases is the luminous object, and the other the luminous object on the screen—that is, the image. Hence, if the screen is perpendicular to the right line joining the centre of

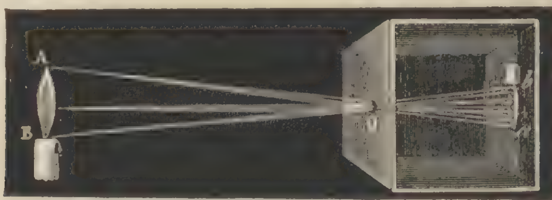


Fig. 337.

the aperture and the centre of the luminous body, the image is similar to the body ; but if the screen is oblique, the image is elongated in the direction of its obliquity. This is what is seen in the shadow produced by foliage ; the luminous rays passing through the leaves produce images of the sun, which are either round or elliptical, according as the ground is perpendicular or oblique to the solar rays, and this is the case whatever be the shape of the aperture through which the light passes.

458. **Velocity of light.**—Light moves with such a velocity that at the surface of the earth there is, to ordinary observation, no appreciable interval between the occurrence of any luminous phenomenon and its perception by the eye. And accordingly, this velocity was first determined by means of astronomical observations. Römer, a Danish astronomer, in 1675, first deduced the velocity of light from an observation of the eclipses of Jupiter's first satellite.

Jupiter is a planet, round which four satellites revolve as the moon does round the earth. This first satellite, E (fig. 338), suffers occultation—that

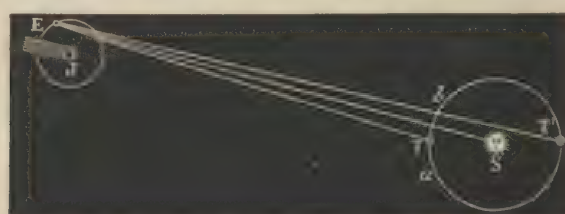


Fig. 338.

is, passes into Jupiter's shadow—at equal intervals of time, which are 42h. 28m. 36s. While the earth moves in that part of its orbit, *ab*, nearest Jupiter, its distance from that planet does not materially alter, and the intervals between two successive occultations of the satellite are approximately the same ; but in proportion as the earth moves away in its revolution round the sun, S, the interval between two occultations increases, and when, at the end of six months, the earth has passed from the position

T to the position T′, a *total* retardation of 16m. 36s. is observed between the time at which the phenomenon is seen and that at which it is calculated to take place. But when the earth was in the position T, the sun's light reflected from the satellite E had to traverse the distance ET, while in the second position the light had to traverse the distance ET′. This distance exceeds the first by the quantity TT′, for from the great distance of the satellite E, the rays ET and ET′ may be considered parallel. Consequently, light requires 16m. 36s. to travel the diameter TT′ of the terrestrial orbit, or twice the distance of the earth from the sun, which gives for its velocity 190,000 miles in a second.

The stars nearest the earth are separated from it by at least 206,265 times the distance of the sun. Consequently, the light which they send requires $3\frac{1}{4}$ years to reach us. Those stars which are only visible by means of the telescope, are possibly at such a distance that thousands of years would be required for their light to reach our planetary system. They might have been extinguished for years without our knowing it.

459. **Foucault's apparatus for determining the velocity of light.**— Notwithstanding the prodigious velocity of light, M. Foucault has succeeded in determining it experimentally by the aid of an ingenious apparatus, based on the use of the rotating mirror, which has been adopted by Mr. Wheatstone in measuring the velocity of electricity.

In the description of this apparatus, a knowledge of the principal properties of mirrors and of lenses is presupposed. Figure 359 represents the

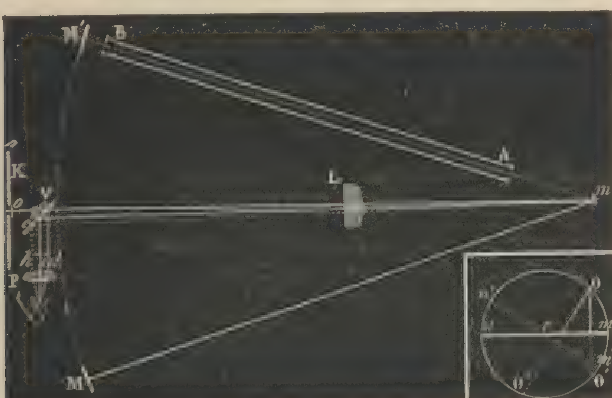


Fig. 339. Fig. 340.

principal parts of M. Foucault's arrangement. The window shutter, K, of a dark chamber is perforated by a square aperture, behind which a platinum wire, *o*, is stretched vertically. A beam of solar light reflected from the outside upon a mirror enters the dark room by the square aperture, meets the platinum wire, and then traverses an achromatic lens, L, with a long focus, placed at a distance from the platinum wire less than double the

principal focal distance. The image of the platinum wire, more or less magnified, would thus be formed on the axis of the lens; but the luminous pencil having traversed the lens, impinges on a plane mirror, *m*, rotating with great velocity; it is reflected from this, and forms in space an image of the platinum wire, which is displaced with an angular velocity double that of the mirror.* This image is reflected by a concave mirror, M, whose centre of curvature coincides with the axis of rotation of the mirror *m*, and with its centre of figure. The pencil reflected from the mirror M returns upon itself, is again reflected from the mirror *m*, traverses the lens a second time, and forms an image of the platinum wire, which appears on the wire itself so long as the mirror *m* turns slowly.

In order to see this image without hiding the pencil which enters by the aperture K, a mirror of unsilvered glass, V, with parallel faces, is placed between the lens and the wire, and is inclined so that the reflected rays fall upon a powerful eyepiece, P.

The apparatus being arranged, if the mirror *m* is at rest, the ray after meeting M is reflected to *m*, and from thence returns along its former path, till it meets the glass plate V in *a*, and being partially reflected, forms at *d*—the distance *ad* being equal to *ao*—an image of the wire, which the eye is enabled to observe by means of the eyepiece P. If the mirror, instead of being fixed, is moving slowly round—its axis being at right angles to the plane of the paper—there will be no sensible change in the position of the mirror *m* during the brief interval elapsing while light travels from *m* to M and back again, but the image will alternately disappear and reappear. If now the velocity of *m* is increased to upwards of 30 turns per second, the interval between the disappearance and reappearance is so short that the impression on the eye is persistent, and the image appears perfectly steady.

Lastly, if the mirror turns with sufficient velocity, there is an appreciable change in its position during the time which the light takes in making the double journey from *m* to M, and from M to *m*; the return ray, after its reflection from the mirror *m*, takes the direction *mb*, and forms its image at *i*; that is, the image has undergone a total deviation, *di*. Speaking precisely, there is a deviation as soon as the mirror turns, even slowly, but it is only appreciable when it has acquired a certain magnitude, which is the case when the velocity of rotation is sufficiently rapid, or the distance M*m* sufficiently great, for the deviation necessarily increases with the time which the light takes in returning on its own path.

In M. Foucault's experiment the distance M*m* was only $13\frac{1}{2}$ feet; when the mirror rotated with a velocity of 600 to 800 turns in a second, deviations of $\frac{2}{10}$ to $\frac{3}{10}$ of a millimeter were obtained.

If $Mm = l$, $Lm = l'$, $oL = r$, and representing by n the number of turns

* To prove this, let *mn* (fig. 360) be the rotating mirror, O a fixed object placed in front, and forming its image at O′. When the mirror comes into the position *m′n′*, the image is formed at O″. But the arc O′*m* equals the arc O*m*, and the arc O″*m′* equals the arc O*m′*; hence the arcs OO′, OO″, are respectively double the arc O*m*, O*m′*. Therefore, by subtraction, the arc O′O″ is double the arc *mm′*, or the angular velocity of the image is double that of the mirror.

in a second, by δ the absolute deviation *di*, and by V the velocity of light, M. Foucault arrived at the formula

$$V = \frac{8\pi l^2 nr}{(\delta l + l')}$$

from which the velocity of light is calculated at 185,157 miles in a second; this number, which is less than that ordinarily assumed, agrees remarkably well with the value deduced from the new determination of the value of the solar parallax.

In this apparatus liquids can be experimented upon. For that purpose a tube, AB, 10 feet long, and filled with distilled water, is placed between the turning mirror *m*, and a concave mirror M′, identical with the mirror M. The luminous rays reflected by the rotating mirror, in the direction *m*M′, traverse the column of water AB twice before returning to V. But the return ray then becomes reflected at *c*, and forms its image at *h*; the deviation is consequently greater for rays which have traversed water than for those which have passed through air alone; hence the velocity of light is less in water than in air.

This is the most important part of these experiments. For it had been shown theoretically that on the undulatory theory the velocity of light must be less in the more highly refracting medium, while the very opposite is a necessary consequence of the emission theory. Hence Foucault's result may be regarded as a crucial test of the validity of the undulatory theory.

The mechanism which M. Foucault uses to turn the mirror with great velocity consists of a small steam turbine, bearing a sort of resemblance to the syren, and, like that instrument, giving a higher sound as the rotation is more rapid; in fact, it is by the pitch of the note that the velocity of the rotation is determined.

460. **Experiments of M. Fizeau.**—In 1849 M. Fizeau measured directly the velocity of light, by ascertaining the time it took to travel from Suresnes to Montmartre and back again. The apparatus employed was a toothed wheel, capable of being turned more or less quickly, and with a velocity that could be exactly ascertained. The teeth were made of precisely the same width as the intervals between them. The apparatus being placed at Suresnes, a pencil of parallel rays was transmitted through an interval between two teeth to a mirror placed at Montmartre. The pencil, directed by a properly-arranged system of tubes and lenses, returned to the wheel. As long as the apparatus was at rest the pencil returned exactly through the same interval as that through which it first set out. But when the wheel was turned sufficiently fast, a tooth was made to take the place of an interval, and the ray was intercepted. By causing the wheel to turn more rapidly, it reappeared when the interval between the next two teeth had taken the place of the former tooth at the instant of the return of the pencil.

The distance between the two stations was 28,334 ft. By means of the data furnished by this distance, by the dimensions of the wheel, its velocity of rotation, etc., M. Fizeau found the velocity of light to be

196,000 miles per second, a result agreeing with that given by astronomical observation as closely as can be expected in a determination of this kind.

461. **Laws of the intensity of light.**—The *intensity* of illumination is the quantity of light received on the unit of surface ; it is subject to the following laws :—

I. *The intensity of illumination on a given surface is inversely as the square of its distance from the source of light.*

II. *The intensity of illumination which is received obliquely is proportional to the cosine of the angle which the luminous rays make with the normal to the illuminated surface.*

In order to demonstrate the first law, let there be two circular screens, CD and AB (fig. 341), one placed at a certain distance from a source of light, L, and the other at double this distance, and let s and S be the

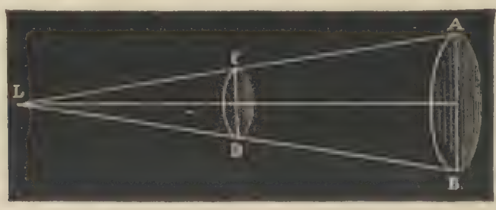


Fig. 341.

areas of the two screens. If a be the total quantity of light which is emitted by the source in the direction of the cone ALB, the intensity of the light on the screen CD, that is, the quantity which falls on the unit of surface, is $\frac{a}{s}$, and the intensity on the screen AB is $\frac{a}{S}$. Now, as the triangles ALB and CLD are similar, the diameter of AB is double that of CD ; and as the surfaces of circles are as the squares of their diameters, the surface S is four times s, consequently the intensity $\frac{a}{S}$ is one-fourth of $\frac{a}{s}$.

The same law may also be demonstrated by an experiment with the apparatus represented in fig. 343. It is made by comparing the shadows of an opaque rod cast upon a glass plate, in one case by the light of a single candle, and in another by that of four candles, placed at double the distance of the first. In both cases the shadows have the same intensity.

Figure 341 shows that it is owing to the divergence of the luminous rays emitted from the same source that the intensity of light is inversely as the square of the distance. The illumination of a surface placed in a beam of parallel luminous rays is the same at all distances, at any rate in a vacuum, for in air and in other transparent media the intensity of light decreases in consequence of absorption, but far more slowly than the square of the distance.

The second law of intensity corresponds to the law which we have found to prevail for heat: it may be theoretically deduced as follows: let DA, EB (fig. 342) be a pencil of parallel rays falling obliquely on a surface, AB, and let *om* be the normal to this surface. If S is the section of the pencil, *a* the total quantity of light which falls on the surface AB, and I that which falls on the unit of surface (that is, the intensity of

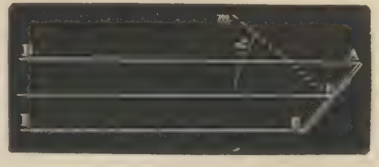


Fig. 342.

illumination), we have $I = \frac{a}{AB}$. But as S is only the projection of AB on a plane perpendicular to the pencil, we know from trigonometry that $S = AB \cos \alpha$, from which $AB = \frac{S}{\cos \alpha}$. This value, substituted in the above equation, gives $I = \frac{a}{S} \cos \alpha$, a formula which demonstrates the law of the cosine, for as a and S are constant quantities, I is proportional to $\cos \alpha$.

The law of the cosine applies also to rays emitted obliquely by a luminous surface; that is, the rays are less intense in proportion as they are more inclined to the surface which emits them. In this respect they correspond to the third law of the intensity of radiant heat.

462. **Photometers.**—A *photometer* is an apparatus for measuring the relative intensities of light.

Rumford's photometer. This consists of a ground glass screen, in front of which is fixed an opaque rod (fig. 343); the lights to be compared—for

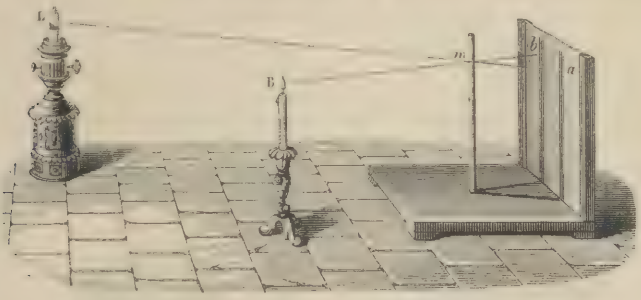


Fig. 343.

instance, a lamp and a candle—are placed at a certain distance in such a manner that each projects on the screen a shadow of the rod. The shadows thus projected are at first of unequal intensity, but by altering the position of the lamp, it may be so placed that the intensity of the two shadows is the same. Then, since the shadow thrown by the lamp is illuminated by the candle, and that thrown by the candle is illuminated by the lamp, the illumination of the screen due to each light is the same.

The intensities of the two lights, that is, the illuminations which they would give at equal distances, are then directly proportional to the squares of their distances from the shadows; that is to say, that if the lamp is three times the distance of the candle, its illuminating power is nine times as great.

For if i and i' are the intensities of the lamp and the candle at the unit of distance, and d and d' their distances from the shadows, it follows, from the first law of the intensity of light, that the intensity of the lamp at the distance d is $\frac{i}{d^2}$, and that of the candle $\frac{i'}{d'^2}$ at the distance d'. On the screen these two intensities are equal; hence $\frac{i}{d^2}=\frac{i'}{d'^2}$, or $\frac{i}{i'}=\frac{d^2}{d'^2}$; which was to be proved.

Bunsen's photometer. When a grease spot is made on a piece of bibulous paper, the part appears translucent. If the paper be illuminated by a light placed in front, the spot appears darker than the surrounding space; if, on the contrary, it be illuminated from behind, the spot appears light on a dark ground. If the greased part and the rest appear unchanged, the intensity of illumination on both sides is the same. Bunsen's photometer depends on an application of this principle. A circular spot is made on a paper screen by means of a solution of spermaceti in naphtha; behind this is placed a light of a certain intensity, which serves as a standard; in this country it is usually a wax candle of known dimensions. The light to be tested is then moved in a right line to such a distance in front of the diaphragm, that there is no difference in brightness between the greased part and the rest of the screen. By measuring the distances of the lights from the screen, their relative illuminating powers are deduced from what has been previously said.

By this kind of determination great accuracy cannot be attained, more especially when the lights to be compared are of different colours, one, for instance, being yellow, and the other of a bluish tint. In this case, the determination of the relative brightness is quite uncertain.

Wheatstone's photometer. The principal part of this instrument is a steel bead, P (fig. 344), fixed on the edge of a disc, which rotates on a pinion, o, working in a larger toothed wheel. The wheel fits in a cylindrical copper box, which is held in one hand, while the other works a

Fig. 344.

Fig. 345.

handle, A, which turns a central axis, the motion of which is transmitted by a spoke, a, to the pinion o. In this way the latter turns on itself, and at the same time revolves round the circumference of the box; the bead

shares this double motion, and consequently describes a curve in the form of a rose (fig. 345).

Now, let M and N be the two lights whose intensities are to be compared; the photometer is placed between them and rapidly rotated. The brilliant points produced by the reflection of the light on the two opposite sides of the bead give rise to two luminous bands, arranged as represented in fig. 345. If one of them is more brilliant than the other—that which proceeds from the light M, for instance—the instrument is brought nearer the other light until the two bands exhibit the same brightness. The distance of the photometer from each of the two lights being then measured, their intensities are proportional to the squares of the distances.

CHAPTER II.

REFLECTION OF LIGHT. MIRRORS.

463. **Laws of the reflection of light.**—When a luminous ray meets a polished surface, it is reflected according to the following two laws, which, as we have seen, also prevail for heat :—

I. *The angle of reflection is equal to the angle of incidence.*

II. *The incident and the reflected ray are both in the same plane, which is perpendicular to the reflecting surface.*

The words are here used in the same sense as in article 357, and need no further explanation.

First proof. The two laws may be demonstrated by the apparatus represented in fig. 346. It consists of a graduated circle in a vertical plane. Two brass slides move round the circumference; on one of them there is a piece of ground glass, P, and on the other an opaque screen, N, in the centre of which is a small aperture. Fixed to the latter slide there is also a mirror, M, which can be more or less inclined, but always remains in a plane perpendicular to the plane of the graduated circle. Lastly, there is a small polished metallic mirror, *m*, placed horizontally in the centre of the circle.

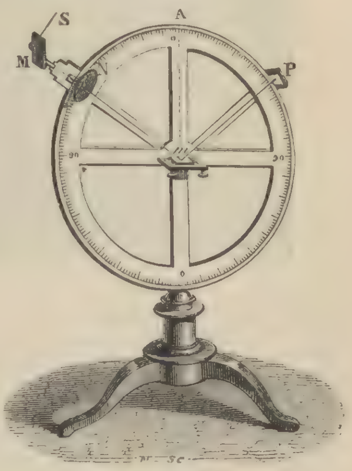


Fig. 346.

In making the experiment, a pencil of solar light, S, is caused to impinge on the mirror M, which is so inclined that the reflected light passes through the aperture in N, and falls on the centre of the mirror *m*.

The luminous pencil then experiences a second reflection in a direction *m*P, which is ascertained by moving P until an image of the aperture is found in its centre. The number of degrees comprised in the arc AN is then read off, and likewise that in AP; these being equal, it follows that the angle of reflection A*m*P is equal to the angle of incidence A*m*M.

The second law follows from the arrangement of the apparatus, the plane of the rays M*m* and *m*P being parallel to the plane of the graduated circle, and, consequently, perpendicular to the mirror *m*.

Second Proof. The law of the reflection of light may also be demonstrated by the following experiment, which is susceptible of greater accuracy than that just described. In the centre of a graduated circle, M (fig. 347), placed in a vertical position, there is a small telescope movable in a plane parallel to the limb; at a suitable distance there is a vessel full of mercury, which forms a perfectly horizontal plane mirror. Some particular star of the first or second magnitude is viewed through the telescope in the direction AE, and the telescope is then inclined so as to receive the ray AD coming from the star after being reflected from the brilliant surface of the mercury. In this way the two angles formed by the rays EA and DA, with the horizontal AH, are found to be equal, from which it

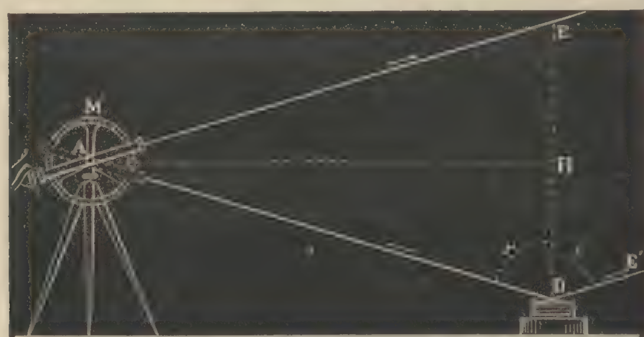


Fig. 347.

may easily be shown that the angle of incidence E′DE is equal to the angle of reflection EDA. For if DE is the normal to the surface of the mercury, it is perpendicular to AH, and AED, ADE are the complements of the equal angles EAH, DAH: therefore AED, ADE are equal; but the two rays AE and DE′ may be considered parallel, in consequence of the great distance of the star, and therefore the angles EDE′ and DEA are equal, for they are alternate angles, and, consequently, the angle EDE′ is equal to the angle EDA.

REFLECTION OF LIGHT FROM PLANE SURFACES.

464. **Mirrors. Images.**—*Mirrors* are bodies with polished surfaces, which show by reflection objects presented to them. The place at which ob-

jects appear is their *image*. According to their shape, mirrors are divided into *plane*, *concave*, *convex*, *spherical*, *parabolic*, *conical*, etc.

465. **Formation of images by plane mirrors.**—The determination of the position and size of images resolves itself into investigating the images of a series of points. And first, the case of a single point, A, placed before a plane mirror, MN (fig. 348), will be considered. Any ray, AB, incident from this point on the mirror, is reflected in the direction BO, making the angle of reflection DBO equal to the angle of incidence DBA.

If now a perpendicular, AN, be let fall from the point A on the mirror, and if the ray OB be prolonged below the mirror until it meets this perpendicular on the point *a*, two triangles are formed, ABN and BN*a*, which are equal, for they have the side BN common to both, and the angles ANB, ABN, equal to the angles *a*NB, *a*BN ; for the angles ANB and *a*NB are right angles, and the angles ABN and *a*BN are equal to the angle OBM. From the equality of these triangles, it follows that *a*N is equal to AN ; that is, that any ray, AB, takes such a direction after being reflected, that its prolongation below the mirror cuts the perpendicular A*a* in the point *a*, which is at the same distance from the mirror as the point

Fig. 348.

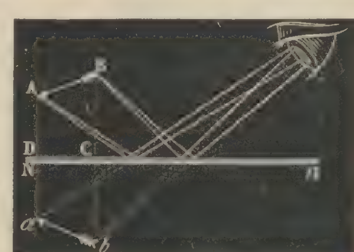


Fig. 349.

A. This applies also to the case of any other ray from the point A—AC, for example. From this the important consequence follows, that all rays from the point A, reflected from the mirror, *follow, after reflection, the same direction as if they had all proceeded from the point a.* The eye is deceived, and sees the point A at *a*, as if it were really situated at *a*. Hence in plane mirrors *the image of any point is formed behind the mirror at a distance equal to that of the given point, and on the perpendicular let fall from this point on the mirror.*

It is manifest that the image of any object will be obtained by constructing according to this rule the image of each of its points, or, at least, of those which are sufficient to determine its form. Fig. 349 shows how the image *ab* of any object, AB, is formed.

It follows from this construction that in plane mirrors *the image is of the same size as the object*, for if the trapezium ABCD be applied to the trapezium DC*ab*, they are seen to coincide, and the object AB agrees with its image.

A further consequence from the above construction is, that in plane

mirrors the image is symmetrical in reference to the object, and not inverted.

466. **Virtual and real images.**—There are two cases relative to the direction of rays reflected by mirrors, according as the rays after reflection are convergent or divergent. In the first case the reflected rays do not meet, but if they are supposed to be produced on the other side of the mirror, their prolongations coincide in the same point, as shown in figs. 348 and 349. The eye is then affected, just as if the rays proceeded from this point, and it sees an image. But the image has no real existence, the luminous rays do not come from the other side of the mirror ; this appearance is called the *virtual image*. The images of real objects produced by plane mirrors are of this kind.

In the second case, where the reflected rays converge, of which we shall soon have an example in concave mirrors, the rays coincide at a point in front of the mirror, and on the same side as the object. They form there an image called the *real image*, for it can be received on a screen. The distinction may be expressed by saying that *real images are those formed by the reflected rays themselves, and virtual images those formed by their prolongations.*

467. **Multiple images formed by glass mirrors.**—Metallic mirrors which have but one reflecting surface only give one image ; glass mirrors give rise to several images, which are readily observed when the image of a candle is looked at obliquely in a looking-glass. A very feeble image is first seen, and then a very distinct one; behind this there are several others, whose intensities gradually decrease until they disappear.

Fig. 350.

This phenomenon arises from the looking-glass having two reflecting surfaces. When the rays from the point A meet the first surface, a part is reflected and forms an image, *a*, of the point A, on the prolongation of the ray *b*E, reflected by this surface ; the other part passes into the glass, and is reflected at *c*, from the layer of metal which covers the hinder surface of the glass, and reaching the eye in the direction *d*H, gives the image *a′*. This image is distant from the first by double the thickness of the glass. It is more intense, because metal reflects better than glass.

In regard to the other images it will be remarked, that whenever light is transmitted from one medium to another, for instance, from glass to air, only some of the rays get through, the remainder are reflected at the surface which bounds the two media. Consequently when the pencil *cd*, reflected from *c*, attempts to leave the glass at *d*, most of the rays composing it pass into the air, but some are reflected at *d*, and continue within the glass. These are again reflected by the metallic surface, and form a third image of A ; after this reflection they come to MN, when many emerge and render the third image visible, but some are again reflected within the glass, and in a similar manner give rise to a fourth, fifth, etc. image,

thereby completing the series above described. It is manifest from the above explanation that each image must be much feebler than the one preceding it, and consequently not more than a small number are visible —ordinarily not more than eight or ten in all.

This multiplicity of images is objectionable in observations, and, accordingly, metallic mirrors are preferable in optical instruments.

468. **Multiple images from two plane mirrors.**—When an object is placed between two plane mirrors, which form an angle with each other, either right or acute, images of the object are formed, the number of which increases with the inclination of the mirrors. If they are at right angles to each other, three images are seen, arranged as represented in fig. 351. The rays OC and OD from the point O, after a single reflection, give the one an image O′, and the other image O″, while the ray OA, which has undergone two reflections at A and B, gives a third image, O‴. When the angle of the mirrors is 60°, five images are produced, and seven if it is 45°. The number of images continues to increase in proportion as the angle diminishes, and when it is zero, that is, when the mirrors are parallel, the number of images is theoretically infinite. This multiplicity arises from the fact that the luminous rays undergo an increasing number of reflections from one mirror to the other.

Fig. 351.

The *kaleidoscope*, invented by Sir D. Brewster, depends on this property of inclined mirrors. It consists of a tube, in which are three mirrors inclined at 60°; one end of the tube is closed by a piece of ground glass, and the other by a cap provided with an aperture. Small irregular pieces of coloured glass are placed at one end between the ground glass and another glass disc, and on looking through the aperture, the other end being held towards the light, the objects and their images are seen arranged in beautiful symmetrical forms; by turning the tube an endless variety of these shapes is obtained.

469. **Irregular reflection.**—The reflection from the surfaces of polished bodies, the laws of which have just been stated, is called the *regular* or *specular reflection*; but the quantity thus reflected is less than the incident light. The light incident on an opaque body actually separates into three parts; one is reflected regularly, another *irregularly*, that is, in all directions; while a third is extinguished, or absorbed by the reflecting body. If light falls on a transparent body, a considerable portion is transmitted with regularity.

The irregularly reflected light is called *scattered light*: it is that which makes bodies visible. The light which is reflected regularly does not give us the image of the reflecting surface, but that of the body from which the light proceeds. If, for example, a solar beam be incident on a well-polished mirror in a dark room, the more perfectly the light is reflected the less

visible is the mirror in the different parts of the room. The eye does not perceive the image of the mirror, but that of the sun. If the reflecting power of the mirror be diminished by sprinkling on it a light powder, the solar image becomes feebler, and the mirror is visible from all parts of the room. Perfectly smooth, polished reflecting surfaces, if such there were, would be invisible.

470. **Intensity of reflected light.**—The intensity of the reflecting power of a body increases with the degree of polish and with the obliquity of the incident ray. For instance, if a sheet of white paper be placed before a candle, and be looked at very obliquely, an image of the flame is seen by reflection, which is not the case if the eye receives less oblique rays.

The intensity of the reflection varies with different bodies, even when the degree of polish and the angle of incidence are the same. It also varies with the nature of the medium which the ray is traversing before and after reflection. Polished glass immersed in water loses a great part of its reflecting power.

REFLECTION OF LIGHT FROM CURVED SURFACES.

471. **Spherical mirrors.**—It has been already stated (464) that there are several kinds of curved mirrors ; those most frequently employed are spherical and parabolic mirrors.

Spherical mirrors are those whose curvature is that of a sphere ; their surface may be supposed to be formed by the revolution of an arc, MN (fig. 352), about the radius CA, which unites the middle of the arc to the centre of the circle of which it is a part. According as the reflection takes place from the internal or the external face of the mirror it is said to be *concave* or *convex*. C, the centre of the hollow sphere, of which the mirror forms part, is called the *centre of curvature* or *geometrical centre :* the point A is the centre of the figure. The infinite right line, AL, which passes through A and C, is the *principal axis* of the mirror : any right line which simply passes through the centre C, and not through the point A, is a *secondary* axis. The angle MCN, formed by joining the centre and extremities of the mirror, is the *aperture*. A *principal* or *meridional section* is any section made by a plane through its principal axis. In speaking of mirrors those lines alone will be considered which lie in the same principal section.

The theory of the reflection of light from curved mirrors is easily deduced from the laws of reflection from plane mirrors, by considering the surface of the former as made up of an infinitude of extremely small plane surfaces, which are its *elements*. The normal to the curved surface at a given point is the perpendicular to the corresponding element, or, what is the same thing, to its corresponding tangent plane. It is shown in geometry that in spheres all the normals pass through the centre of curvature, so that the normal may readily be drawn to any point of a spherical mirror.

472. **Focus of a spherical concave mirror.**—In a curved mirror the *focus* is a point in which the reflected rays meet or tend to meet if pro-

duced either backwards or forwards ; there may either be a *real focus* or a *virtual focus.*

Real focus. We shall first consider the case in which the luminous rays are parallel to the principal axis, which presupposes that the luminous body is at an infinite distance ; let GD (fig. 352) be such a ray.

From the hypothesis that curved mirrors are composed of a number of infinitely small plane elements, this ray would be reflected from the element corresponding to the point D, according to the laws of the reflection from plane mirrors (463) ; that is, that CD being the normal at the

Fig. 352.

point of incidence D, the angle of reflection CDF is equal at the angle of incidence GDC, and is in the same plane. It follows from this that the point F, where the reflected ray cuts the principal axis, divides the radius of curvature AC very nearly into two equal parts. For in the triangle DFC, the angle DCF is equal to the angle CDG, for they are alternate and opposite angles ; likewise the angle CDF is equal to the angle CDG, from the laws of reflection ; therefore the angle FDC is equal to the angle FCD, and the sides FC and FD are equal as being opposite to equal angles. Now the smaller the arc, AD, the more nearly does DF equal AF ; and when the arc is only a small number of degrees, the right lines AF and FC may be taken as approximately equal, and the point F may be taken as the middle of AC. So long as the aperture of the mirror does not exceed 8 to 10 degrees, any other ray, HB, will after reflection pass very nearly through the point F. Hence, when a pencil of rays parallel to the axis falls on a concave mirror, the rays intersect after reflection in the same point, which is at an equal distance from the centre of curvature and from the mirror. This point is called the *principal focus* of the mirror, and the distance AF is the *principal focal distance.*

All rays parallel to the axis meet in the point F; and conversely if a luminous object be placed at F, the rays emitted by this object will after reflection take the directions DG, BH, parallel to the principal axis ; for in this case the angles of incidence and reflection have changed places ; but these angles always remain equal.

The case is now to be considered in which the rays are emitted from a luminous point, L (fig. 353), placed on the principal axis, but at such a distance that they are not parallel, but divergent. The angle LKC, which the incident ray LK forms with the normal KC, is smaller than the angle SKC, which the ray SK parallel to the axis forms with the same normal, and, consequently, the angle of reflection corresponding to the ray LK

must be smaller than the angle CKF, corresponding to the ray SK. And, therefore, the ray LK will meet the axis after reflection at a point, *l*, between the centre C and the principal focus F. So long as the aperture of the mirror does not exceed a small number of degrees, all the rays from the point L will intersect after reflection in the point *l*. This point is called the *conjugate focus*, in order to indicate the connection between the points L and *l*. These points are reciprocal to each other, that is, if the luminous point were transferred to *l*, its conjugate focus would be at L, *l*K being the incident and KL the reflected ray.

On considering the figure 353 it will be seen that when the object L is brought near to or removed from the centre C, its conjugate focus ap-

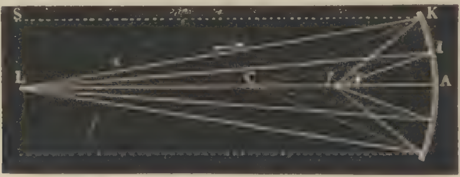


Fig. 353.

proaches or recedes in a corresponding manner, for the angles of incidence and reflection increase or decrease together.

If the object L coincide with the centre C, the angle of incidence is null, and as the angle of reflection must be the same, the ray is reflected on itself, and the focus coincides with the object. When the luminous object is between the centre C and the principal focus, the conjugate focus in turn is on the other side of the centre, and is further from the centre according as the luminous point is nearer the principal focus. If the luminous point coincides with the principal focus, the reflected rays, being parallel to the axis, will not meet, and there is, consequently, no focus.

Virtual focus.—There is, lastly, the case in which the object is placed at L, between the principal focus and the mirror (fig. 354). Any ray, LM, emitted from the point L, makes with the normal CM an angle of incidence, LMC, greater than FMC; the angle of reflection must be

Fig. 354.

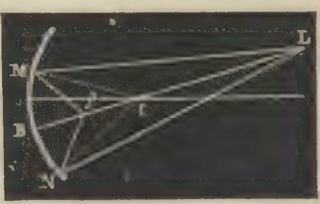


Fig. 355.

greater than CMS, and therefore the reflected ray ME diverges from the axis AK. This is also the case with all rays from the point L, and hence

these rays do not intersect, and, consequently, form no conjugate focus; but if they are conceived to be prolonged on the other side of the mirror, their prolongations will intersect in the same point, *l*, on the axis, and the eye experiences the same impression as if the rays were emitted from the point *l*. Hence a *virtual focus* is formed quite analogous to those formed by plane mirrors (466).

In all these cases it is seen that the position of the principal focus is constant, while that of the conjugate foci and of the virtual foci vary. *The principal and the conjugate foci are always on the same side of the mirror as the object*, while *the virtual focus is always on the other side of the mirror.*

Hitherto the luminous point has always been supposed to be placed on the principal axis itself, and then the focus is formed on this axis. In the case in which the luminous point is situate on a secondary axis, LB (fig. 355), by applying to this axis the same reasoning as in the preceding case, it will be seen that the focus of the point L is formed at a point *l*, on the secondary axis, and that, according to the distance of the point L, the focus may be either principal, conjugate, or virtual.

473. **Foci of convex mirrors.**—In convex mirrors there are only virtual foci. Let SI, TK . . . (fig. 356) be rays parallel to the principal axis of a convex mirror. These rays, after reflection, take the diverging directions IM, KH, which, when continued, meet in a point, F, which is the

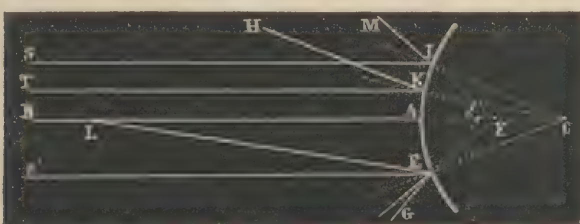


Fig. 356.

principal virtual focus of the mirror. By means of the triangle CKF, it may be shown in the same manner as with concave mirrors, that the point F is approximately the middle of the radius of curvature, CA.

If the incident luminous rays, instead of being parallel to the axis, proceed from a point, L, situated on the axis at a finite distance, it is at once seen that a virtual focus will be formed between the principal focus F and the mirror.

474. **Determination of the principal focus.**—In the applications of concave and convex mirrors it is often necessary to know the radius of curvature. This is tantamount to finding the principal focus; for being situated at the middle of the radius, it is simply necessary to double the focal distance.

To find this focus with a concave mirror, it is exposed to the sun's rays, so that its principal axis is parallel to them, and then with a small screen

of ground glass the point is sought at which the image is formed with the greatest intensity: this is the principal focus. The radius of the mirror is double this distance.

If the mirror is convex it is covered with paper, but two small portions, H and I, are left exposed at equal distances from the centre of the figure A, and on the same principal section (fig. 357). A screen, MN, in the centre of which is an opening larger than the distance HI, is placed before the mirror. If a pencil of solar rays, SH, S′I, parallel to the axis, fall on the mirror, the light is reflected at H and I, on the parts where the mirror is left exposed, and forms on the screen two brilliant images at *h* and *i*. By moving the screen MN nearer to or farther from the mirror, a

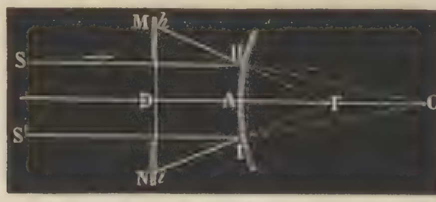


Fig. 357.

position is found at which the distance *hi* is double that of HI. The distance AD from the screen to the mirror then equals the principal focal distance. For the arc HAI does not sensibly differ from its chord, and because the triangles FHI and F*hi* are similar, $\frac{HI}{hi} = \frac{FA}{FD}$; but HI is half of *hi*, and therefore also FA is the half of FD, and therefore AD is equal to AF. Further, FA is the principal focal distance; for the rays SH and S′I are parallel to the axis: consequently also twice the distance AD equals the radius of curvature of the mirror.

475. **Formation of images in concave mirrors.**—Hitherto it has been supposed that the luminous or illuminated object placed in front of the mirror was simply a point; but if this object has a certain magnitude, we can conceive a secondary axis drawn through each of its points, and thus a series of real or virtual foci could be determined, the collection of which composes the image of the object. By the aid of the constructions which have served for determining the foci, we shall investigate the position and magnitude of these images in concave and in convex mirrors.

Real image.—We shall first take the case in which the mirror is concave, and the object AB (fig. 358) is on the other side of the centre. To obtain the image or the focus of any point, A, a secondary axis, AE, is drawn from this point, and then drawing from the point A an incident ray, AD, the normal to this point, CD, is taken, and the angle of reflection CD*a* is made equal to the angle of incidence ADC. The point *a*, where the reflected ray cuts the secondary axis AE, is the conjugate focus of the point A, because every other ray drawn from this point passes through with *a*. Similarly if a secondary axis, BI, be drawn from the

point B, the rays from this point meet after reflection in *b*, and form the conjugate focus of B. And as the images of all the points of the object are formed between *a* and *b*, *ab* is the complete image of AB. From what has been said about foci (472), it appears that *this image is real, inverted, smaller than the object, and placed between the centre of curvature and the principal focus.* This image may be seen in two ways; by placing

Fig. 358.

the eye in the continuation of the reflected rays, and then it is an aërial image which is seen; or the rays are collected on a screen, on which the image appears to be depicted.

If the luminous or illuminated object is placed at *ab*, between the principal focus and the centre, its image is formed at AB. It is then a real but inverted image; it is greater than the object, *and the greater as the object, ab, is nearer the focus.*

If the object is placed in the principal focus itself, no image is produced; for then the rays emitted from each point form, after reflection, as many pencils respectively parallel to the secondary axis, which is

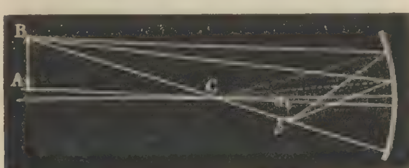


Fig. 359.

drawn through the point from which they are emitted (472), and hence neither foci nor images are formed.

When all points of the object AB are above the principal axis (fig. 359), by repeating the preceding construction, it is readily seen that the image of the object is formed at *ab*.

Virtual image.—The case remains in which the object is placed between the principal focus and the mirror. Let AB be this object (fig. 360); the incident rays after reflection take the directions DI and KH, and their prolongations form a virtual image, *a*, of the point A, on the secondary axis. Similarly, an image of B is formed at *b*, consequently the eye sees at *ab* the image of AB. *This image is virtual, erect, and larger than the object.*

From what has been stated, it is seen that according to the distance of the object concave mirrors produce two kinds of images, or none at all ; a person notices this by placing himself before a concave mirror. At a

Fig. 360.

certain distance he sees an image of himself inverted and smaller : this is the real image : at a less distance the image becomes confused, and disappears when he is at the focus ; still nearer the image appears erect, but larger—it is a virtual image.

476. **Formation of images in convex mirrors.**—Let AB (fig. 361) be an object placed before a mirror at any given distance. AC and BC are secondary axes, and it follows from what has been already stated, that all the rays from A are divergent after reflection, and that their

Fig. 361.

prolongations pass through a point, *a*, which is the virtual image of the point A. Similarly the rays from B form a virtual image of it in the point *b*. The eye which receives the divergent rays DE, KA, . . . sees in *ab* an image of AB. Hence, whatever the position of an object before a convex mirror, *the image is always virtual, erect, and smaller than the object.*

477. **Formulæ for spherical mirrors.**—The relation between the position of an object and that of its image in spherical mirrors may be

Fig. 362.

expressed by a very simple formula. In the case of concave mirrors, let R be its radius of curvature, p the distance LA of the object, L (fig. 362),

and p' the distance lA of the image from the mirror. In the triangle LMl, the normal MC divides the angle LMl in two equal parts, and from geometry it follows that the two segments LC, Cl are to each other as the two sides containing the angle; that is, $\frac{Cl}{CL}=\frac{lM}{LM}$: therefore $Cl \times LM = CL \times lM$.

If the arc AM does not exceed 5 or 6 degrees, the lines ML and Ml are approximately equal to AL and Al; that is, to p and p'.

Further, $$Cl = CA - Al = R - p',$$

and also $$CL = AL - AC = p - R.$$

These values substituted in the preceding equations give

$$(R-p')\,p = (p-R)\,p',$$
$$Rp - pp' = pp' - Rp'.$$

From which transposing and reducing we have

$$Rp + Rp' = 2pp' \quad . \quad . \quad . \quad . \quad (1)$$

If the terms of this equation be all divided by $pp'R$, we obtain

$$\frac{1}{p'}+\frac{1}{p}=\frac{2}{R} \quad . \quad . \quad . \quad . \quad (2)$$

which is the usual form of the equation.

From the equation (1) we get

$$p' = \frac{pR}{2p-R} \quad . \quad . \quad . \quad . \quad (3)$$

which gives the distance of the image from the mirror, in terms of the distance of the object, and of the radius of curvature.

478. **Discussion of the formulæ for mirrors.**—We shall now investigate the different values of p', according to the values of p in the formula (3).

i. Let the object be placed at an infinite distance on the axis, in which case the incident rays are parallel. To obtain the value of p', both terms of the fraction (3) must be divided by p, which gives

$$p' = \frac{R}{2-\frac{R}{p}} \quad . \quad . \quad . \quad . \quad (4)$$

as p is infinite, $\frac{R}{p}$ is zero, and we have $p'=\frac{R}{2}$; that is, the image is formed in the principal focus, as ought to be the case, for the incident rays are parallel to the axis.

ii. If the object approaches nearer the mirror, p decreases, and as the denominator of the formula (4) diminishes, the value of p' increases; consequently the image approaches the centre at the same time as the object, but it is always between the principal focus and the centre, for so long as p is $>$R, we have $\frac{R}{2-\frac{R}{p}} > \frac{R}{2}$ and $<$R.

iii. When the object coincides with the centre, $p = R$, and, consequently, $p' = R$; that is, the image coincides with the object.

iv. When the luminous object is between the centre and the principal focus, $p < R$, and hence from the formula (4), $p' > R$; that is, the image is formed on the other side of the centre. When the object is in the focus, $p = \frac{R}{2}$, which gives $p' = \frac{R}{0} = \infty$; that is, the image is at an infinite distance, for the reflected rays are parallel to the axis.

v. Lastly, if the object is between the principal focus and the mirror, we get $p < \frac{R}{2}$; p' is then negative, because the denominator of the formula (4) is negative. Therefore, the distance p' of the mirror from the image must be calculated on the axis in a direction opposite to p. The image is then virtual, and is on the other side of the mirror.

Making p' negative in the formula (2), it becomes $\frac{1}{p} - \frac{1}{p'} = \frac{2}{R}$; in this form it comprehends all cases of virtual images in concave mirrors.

In the case of convex mirrors, the image is always virtual (476); p' and R are of the same sign, since the image and the centre are on the same side of the mirror, while the object being on the opposite side, p is of the contrary sign; hence in the formula (2) we get

$$\frac{1}{p'} - \frac{1}{p} = \frac{2}{R} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

as the formula for convex mirrors. It may also be found directly by the same geometrical considerations as those which have led to the formula (2) for concave mirrors.

It must be observed that the preceding formula are not rigorously true, inasmuch as they depend upon the hypothesis that the lines LM and *l*M (fig. 362) are equal to LA and A*l*; although this is not true, the error diminishes without limit with the angle MCA; and when this angle does not exceed a few degrees, the error is so small that it may, in practice, be neglected.

479. **Calculation of the magnitude of images.**—By means of the above formulæ the magnitude of an image may be calculated, when the

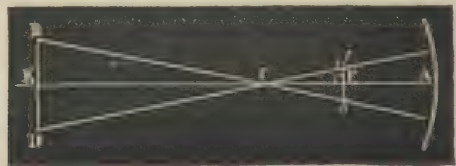


Fig. 363.

distance of the object, its magnitude, and the radius of the mirror are given. For if BD be the object (fig. 363), *bd* its image, and if the distance

KA and the radius AC be known, Ao can be calculated by means of formula (3) of article 477. Ao known, oC can be calculated. But as the triangles BCD and dCb are similar, their bases and heights are in the proportion bd : BD = Co : CK, or

Length of the image : length of the object

= distance from image to centre : distance from the object to centre.

480. **Spherical aberration. Caustics.**—In the foregoing theory of the foci and images of spherical mirrors, it has already been observed that the reflected rays only pass through a single point when the aperture of the mirror does not exceed 8 or 10 degrees (472). With a larger aperture, the rays reflected near the edges meet the axis nearer the mirror than those which are reflected at a small distance from the neighbourhood of the centre of the mirror. Hence arises a want of precision in these images, which is called *spherical aberration* by reflection, to distinguish it from the spherical aberration by refraction, which occurs in the case of lenses.

Every reflected ray cuts the one next to it (fig. 364), and their points of intersection form in space a curved surface, which is called the *caustic by*

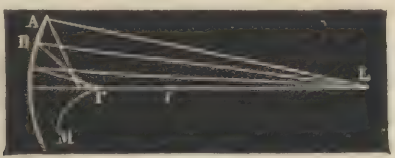


Fig. 364.

reflection. The curve FM represents one of the branches of a section of this surface made by the plane of the paper. When the light of a candle is reflected from the inside of a cup or tumbler, a section of the caustic surface can be seen by partly filling the cup or tumbler with milk.

481. **Applications of mirrors.**—The applications of plane mirrors in domestic economy are well known. Mirrors are also frequently used in physical apparatus for sending light in a certain direction. The solar light can only be sent in a constant direction by making the mirror moveable. It must have a motion which compensates for the continual change in the direction of the sun's rays produced by the apparent diurnal motion of the sun. This result is obtained by means of a clockwork motion, to which the mirror is fixed, and which causes it to follow the course of the sun. This apparatus is called the *heliostat.* The reflection of light is also used to measure the angles of crystals by means of the instruments known as *reflecting goniometers.*

Concave spherical mirrors are also often used. They are applied for magnifying *mirrors*, as in a shaving mirror. They have been employed for burning mirrors, and are still used in telescopes. They also serve as reflectors, for conveying light to great distances, by placing a luminous object in their principal focus. For this purpose, however, parabolic mirrors are preferable.

482. **Parabolic mirrors.**—*Parabolic mirrors* are concave mirrors, whose surface is generated by the revolution of the arc of a parabola, AM, about its axis, AX (fig. 365).

It has been already stated that in spherical mirrors the rays parallel to the axis converge only approximately to the principal focus, and reciprocally when a source of light is placed in the principal focus of these mirrors, the reflected rays are not exactly parallel to the axis. Parabolic mirrors are free from this defect; they are more difficult to construct, but are far better for reflectors. It is a well-known property of a parabola that the right line FM, drawn from the focus F, to any point, M, of the curve, and the line ML, parallel to the axis AF, make equal angles with the tangent TT′ at this point. Consequently, all rays parallel to the axis after reflection meet in the focus of the mirror F, and conversely, when a source of light is placed in the focus, the rays incident on the mirror, are reflected exactly parallel to the axis. The light thus reflected tends to maintain its intensity even at a great distance, for it has been seen (461) that it is the divergence of the luminous rays which principally weakens the intensity of light.

Fig. 365.

It is from this property that parabolic mirrors are used in carriage lamps, and in the lamps placed in front of and behind railway trains. These reflectors were formerly used for lighthouses, but have been replaced by lenticular glasses.


Fig 366.

When two equal parabolic mirrors are cut by a plane perpendicular to the axis passing through the focus, and are then united at their intersections, as shown in the figure 366, so that their foci coincide, a system of reflectors is obtained with which a single lamp illuminates in two directions at once. This arrangement is used in lighting staircases.

CHAPTER III.

SINGLE REFRACTION. LENSES.

483. **Phenomenon of refraction.**—*Refraction* is the deflection which luminous rays experience in passing obliquely from one medium to another; for instance, from air into water. We say obliquely, because if the incident ray is perpendicular to the surface separating the two media, it is not deflected, and continues its course in a right line.

The *incident ray* being represented by SO (fig. 367), the *refracted ray* is the direction OH which light takes in the second medium; and of the angles SOA and HOB, which these rays form with the line AB, at right angles to the surface which separates the two media, the first is the *angle of incidence*, and the other the *angle of refraction*. According as the refracted ray approaches or deviates from the normal, the second medium is said to be more or less *refringent* or *refracting* than the first.

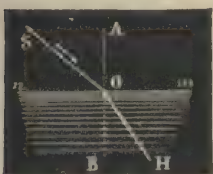


Fig. 367.

All the light which falls on a refracting surface does not completely pass into it; one part is reflected and scattered, while another penetrates into the medium.

Analysis shows that the direction of refraction depends on the relative velocity of light in the two media. On the undulatory theory the more highly refracting medium is that in which the velocity of propagation is least.

In uncrystallised media, such as air, liquids, ordinary glass, the luminous ray is singly refracted; but in certain crystallised bodies, such as Iceland spar, selenite, etc., the incident ray gives rise to two refracted rays. The latter phenomenon is called *double refraction*, and will be discussed in another part of the book. We shall here deal exclusively with *single refraction.*

484. **Laws of single refraction.**—When a luminous ray is refracted in passing from one medium into another of a different refractive power, the following laws prevail:—

I. *Whatever the obliquity of the incident ray, the ratio which the sine of the incident angle bears to the sine of the angle of refraction is constant for the same two media, but varies with different media.*

II. *The incident and the refracted ray are in the same plane which is perpendicular to the surface separating the two media.*

These are known as *Descartes' laws*, and are demonstrated by the same apparatus as that used for the laws of reflection (440). The plane mirror in the centre of the graduated circle is replaced by a semi-cylindrical glass vessel, filled with water to such a height that its level is exactly the height of the centre (fig. 368). If the mirror, M, be then so inclined that a reflected ray, MO, is directed towards the centre, it is refracted on passing into the water, but it passes out without refraction,

because then its direction is at right angles to the curved sides of the vessel. In order to observe the course of the refracted ray, it is received on a screen, P, which is moved until the image of the aperture in the screen N is formed in its centre. In all positions of the screens N and P, the sines of the angles of incidence and refraction are measured by means of two graduated rules, moveable so as to be always horizontal, and hence perpendicular to the diameter AD.

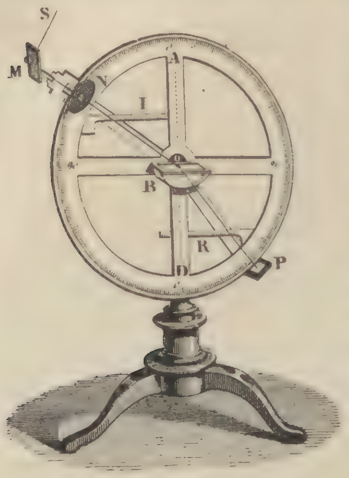


Fig. 368.

On reading off the lengths of the sines of the angles MOA and DOP in the scales I and R, the numbers are found to vary with the position of the screens, but their ratio is constant; that is, if the sine of incidence becomes twice or three times as large, the sine of refraction increases in the same ratio, which demonstrates the first law. The second law follows from the arrangement of the apparatus, for the plane of the graduated limb is perpendicular to the surface of the liquid in the semi-cylindrical vessel.

485. **Index of refraction.**—The ratio between the sines of the incident and refracted angle is called *index of refraction* or *refractive index*. It varies with the media; for example, from air to water it is $\frac{4}{3}$, and from air to glass it is $\frac{3}{2}$.

If the media are considered in an inverse order—that is, if light passes from water to air, or from glass to air—it follows the same course, but in a contrary direction, PO becoming the incident, and OM the refracted ray. Consequently, the index of refraction is reversed; from water to air it is then $\frac{3}{4}$, and from glass to air $\frac{2}{3}$.

486. **Effects produced by refraction.**—In consequence of refraction, bodies immersed in a medium more highly refracting than air appear nearer the surface of this medium, but they appear to be more distant if immersed in a less refracting medium. Let L (fig. 369) be an object immersed in a mass of water. In passing thence into air, the rays LA, LB . . . diverge from the normal to the point of incidence, and assume the direction AC, BD . . . , the prolongations of which intersect approximately in the point L′, placed on the perpendicular L′K. The eye receiving these rays sees the object L at L′. The greater the obliquity of the rays LA, LB . . . the higher the object appears.

It is for the same reason that a stick plunged obliquely into water appears bent (fig. 370), the immersed part appearing raised.

Owing to an effect of refraction, stars are visible to us even when they are below the horizon. For as the layers of the atmosphere are denser

in proportion as they are nearer the earth, and as the refractive power of a gas increases with its density (495), it follows that on entering the

Fig. 369.

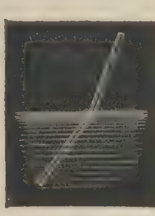


Fig. 370.

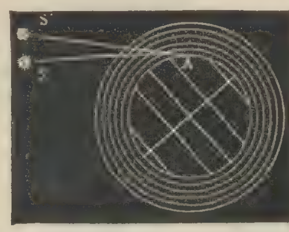


Fig. 371.

atmosphere the luminous rays become bent, as seen in the fig. 371, describing a curve before reaching the eye, so that we see the star at S′ along the tangent of this curve instead of at S. In our climate the atmospheric refraction does not raise the stars when on the horizon more than half a degree.

487. **Total reflection. Critical angle.** — When a luminous ray passes from one medium into another which is less refracting, as from water into air, it has been seen that the angle of incidence is less than the angle of refraction. Hence, when light is propagated in a mass of water from S to O (fig. 372), there is always a value of the angle of incidence SOB, such that the angle of refraction AOR, is a right angle, in which case the refracted ray emerges parallel to the surface of the water.

This angle, SOB, is called the *critical angle*, since for any greater angle, POB, the incident ray cannot emerge, but undergoes an internal reflection, which is called *total reflection*, because the incident light is entirely reflected. From water to air the critical angle is 48° 35′ ; from glass to air, 41° 48′.

The occurrence of this internal reflection may be observed by the following experiment. An object, A, is placed before a glass vessel filled with water (fig. 373) ; the surface of the liquid is then looked at as

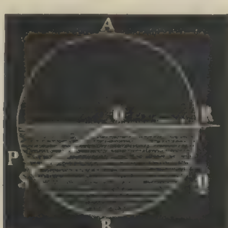


Fig. 372.

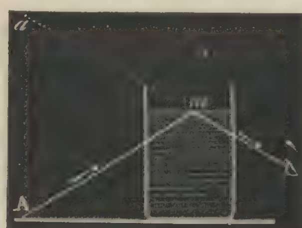


Fig. 373.

shown in the figure, and an image of the object A is seen at *a*, formed by the rays reflected at *m*, in the ordinary manner of a mirror.

Similar effects of the total reflection of the images of objects contained in aquaria are frequently observed, and add much to the interest of their appearance.

488. **Mirage.**—The *mirage* is an optical illusion by which inverted images of distant objects are seen as if below the ground or in the atmosphere. This phenomenon is of most frequent occurrence in hot climates, and more especially on the sandy plains of Egypt. The ground

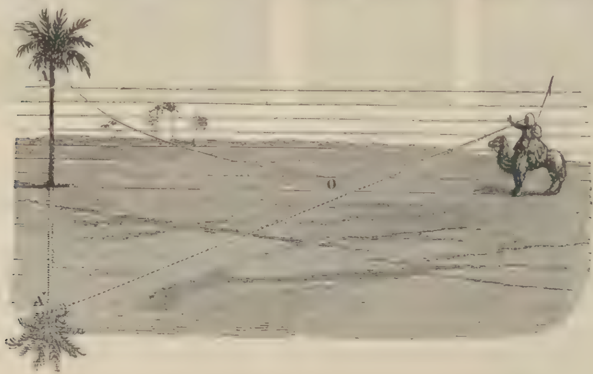


Fig. 374.

there has often the aspect of a tranquil lake, on which are reflected trees and the surrounding villages. The phenomenon has long been known, but Monge, who accompanied Napoleon's expedition to Egypt, was the first to give an explanation of it.

It is a phenomenon of refraction, which results from the unequal density of the different layers of the air when they are expanded by contact with the heated soil. The least dense layers are then the lowest, and a luminous ray from an elevated object, A (fig. 374), traverses layers which are gradually less refracting; for, as will be shown presently (496), the refracting power of a gas diminishes with lessened density. The angle of incidence accordingly increases from one layer to the other, and ultimately reaches the critical angle, beyond which, internal reflection succeeds to refraction (487). The ray then rises, as seen in the figure, and undergoes a series of successive refractions, but in a direction contrary to the first, for it now passes through layers which are gradually more refracting. The luminous ray then reaches the eye with the same direction as if it had proceeded from a point below the ground, and hence it gives an inverted image of the object, just as if it had been reflected at the point O, from the surface of a tranquil lake.

Mariners sometimes see images in the air of the shores or of distant vessels. This is due to the same cause as the mirage, but in a contrary direction, only occurring when the temperature of the air is above that of the sea, for then the inferior layers of the atmosphere are denser, owing to their contact with the surface of the water.

TRANSMISSION OF LIGHT THROUGH TRANSPARENT MEDIA.

489. **Media with parallel faces.**—When light traverses a medium with parallel faces the *emergent* rays are parallel to the incident rays.

Let MN (fig. 375) be a glass plate with parallel faces, let SA be the incident, and DB the emergent ray, i and r the angles of incidence and of refraction at the entrance of the ray, and, lastly, i' and r' the same angles at its emergence. At A the light undergoes a first refraction, the index of which is $\frac{\sin i}{\sin r}$ (485). At D it is refracted a second time, and the index is then $\frac{\sin i'}{\sin r'}$. But we have seen that the index of refraction of glass to air is the reciprocal of its refraction from air to glass; hence

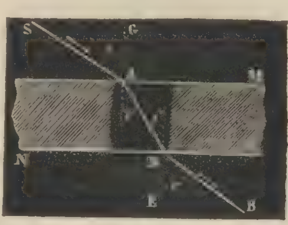


Fig. 375.

$$\frac{\sin i'}{\sin r'} = \frac{\sin r}{\sin i}.$$

But as the two normals AG and DE are parallel, the angles r and i' are equal, as being alternate interior angles. As the numerators in the above equation are equal, the denominators must be also equal; the angles r' and i are therefore equal, and hence DB is parallel to SA.

490. **Prism.**—In optics a *prism* is any transparent medium comprised between two plane faces inclined to each other. The intersection of these two faces is the *edge* of the prism, and their inclination is its refracting angle. Every section perpendicular to the edge is called a *principal section.*

The prisms used for experiments are generally right triangular prisms of glass, as shown in the fig. 376, and their principal section is a triangle (fig. 377). In this section the point A is called the *summit* of the prism, and the right line BC is called the *base*; these expressions have reference to the triangle ABC, and not to the prism.

Fig. 376.

Fig. 377.

491. **Path of rays in prisms.**—When the laws of refraction are known, the passage of rays in a prism is readily determined. Let O be a luminous point (fig. 377) in the same plane as the principal section ABC of a prism, and let OD be an incident ray. This ray is refracted

at D, and approaches the normal, because it passes into a more highly refracting medium. At K it experiences a second refraction, but it then deviates from the normal, for it passes into air, which is less refractive than glass. The light is thus refracted twice in the same direction, so that *the ray is deflected towards the base*, and consequently the eye which receives the emergent ray KH sees the object O at O′; that is, *objects seen through a prism appear deflected towards its summit.* The angle OEO′, which the incident and emergent rays form with each other, expresses the deviation of light caused by the prism, and is called *the angle of deviation.*

Besides this, objects seen through a prism appear in all the colours of the rainbow; this phenomenon will be described under the name of *dispersion.*

492. **Conditions of emergence in prisms.** — In order that any luminous rays refracted at the first face of a prism may emerge from the second, it is necessary that the refractive angle of the prism be less than twice the critical angle of the substance of which the prism is composed. For if LI (fig. 378) be the ray incident on the first face, IE the refracted ray, PI and PE the normals, the ray IE can only emerge from the second face when the incident angle IEP is less than the critical angle (487). But as the incident angle LIN increases, the angle EIP also increases, while IEP diminishes. Hence, according as the direction of the ray LI tends to become parallel with the face AB, does this ray tend to emerge at the second face.

Let LI be now parallel to AB, the angle r is then equal to the critical angle l of the prism, because it has its maximum value. Further, the angle EPK, the exterior angle of the triangle IPE, is equal to $r+i'$; but the angles EPK and A are equal, because their sides are perpendicular, and therefore $A=r+i'$; therefore also $A=l+i'$, for in this case $r=l$. Hence, if $A=2l$ or is $>2l$, we shall have $i'=l$ or $>l$, and therefore the ray would not emerge at the second face, but would undergo internal reflection, and would emerge at a third face, BC. This would be much more the case with rays whose incident angle is less than BIN, because we have already seen that i' continually increases. Thus in the case in which the refracting angle of a prism is equal to $2l$ or is greater, no luminous ray could pass through the faces of the refracting angle.

Fig. 378.

As the critical angle of glass is 41° 48′, twice this angle is less than 90°, and, accordingly, objects cannot be seen through a glass prism whose refracting angle is a right angle. As the critical angle of water is 48° 35′, light could pass through a hollow rectangular prism formed of three glass plates and filled with water.

If we suppose A to be greater than l and less than $2l$, then of rays incident at I some within the angle NIB will emerge from AC, others will not emerge, nor will any emerge that are incident within the angle NIA. If we suppose A to have any magnitude less than l, all rays incident at I within the angle NIB will emerge from AC, as also will some of those incident within the angle NIA.

493. **Minimum deviation.** — When a pencil of solar light passes through an aperture, A, in the side of a dark chamber (fig. 379), the pencil is projected in a straight line, AC, on a distant screen. But if a vertical prism be interposed between the aperture and the screen, the pencil is deviated towards the base of the prism, and the image is projected at D, at some distance from the point C. If the prism be turned, so that the incident angle decreases, the luminous disc approaches the point C, up to a certain position, E, from which it reverts to its original position even when the prism is rotated in the same direction. Hence there is a deviation, EBC, less than any other. It may be demonstrated mathematically that this *minimum deviation* takes place when the angles of incidence and of emergence are equal.

The angle of minimum deviation may be calculated when the incident angle and the refracting angle of the prism are known. For, when the deviation is least, as the angle of emergence r' is equal to the incident angle i (fig. 378), r must $= i'$. But it has been shown above (482) that $A = r + i'$; consequently,

$$A = 2r \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the minimum angle of deviation EDL be called d, this angle being exterior to the triangle DIE, we readily obtain the equation

$$d = i - r + r' - i' = 2i - 2r,$$

whence

$$d = 2i - A \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

which gives the angle d, when i and A are known.

From the formulæ (1) and (2) a third may be obtained, which serves to calculate the index of refraction of a prism, when its refracting angle

Fig. 379.

and the minimum deviation are known. The index of refraction n is the ratio of the sines of the angles of incidence and refraction; hence $n = \frac{\sin i}{\sin r}$; replacing i and r from their values in the above equations (1)

and (2), we get

$$n = \frac{\sin\left(\frac{A+d}{2}\right)}{\sin\frac{A}{2}} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

494. **Measurement of the index of refraction in solids.**—By means of the preceding formula (3) the refractive index of a solid may be calculated when the angles A and *d* are known.

In order to determine the angle A, the substance is cut in the form of a triangular prism, and the angle measured by means of a goniometer (481).

The angle *d* is measured in the following manner: a ray, LI, emitted from a distant object (fig. 380), is received on the prism, which is turned in order to obtain the minimum deviation EDL.′ By means of a telescope with a graduated circle, the angle EDL′ is read off, which the refracted ray DE makes with the ray DL′, coming directly from the

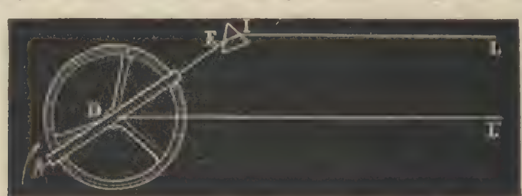


Fig. 380.

object; now this is the angle of minimum deviation, assuming that the object is so distant that the two rays LI and L′D are approximately parallel. These values then only need to be substituted in the equation (3) to give the value of n.

This method is due to Newton. Under many circumstances it cannot be employed; for instance, when the refractive index of a mere drop of fluid is required. In this case, use may be made of a method due to Wollaston, which depends on the determination of the critical angle of the substance.

495. **Measurement of the index of refraction of liquids.**—M. Biot has applied Newton's method to determining the refractive index of liquids. For this purpose a cylindrical cavity, O, of about 0·75 in. in diameter, is perforated in a glass prism, PQ (fig. 381), from the incident face to the face of emergence. This cavity is closed by two plates of glass which are cemented on the sides of this prism. Liquids are introduced through a small stoppered aperture, B. The refracting angle and the minimum deviation of the liquid prism in the cavity O having been determined, their values are introduced into the formula (3), which gives the index.

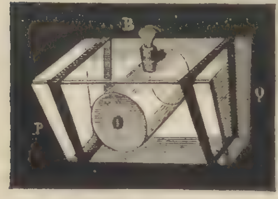


Fig. 381.

496. **Measurement of the index of refraction of gases.**—A method for this purpose founded on that of Newton has been devised by MM. Biot and Arago. The apparatus which they use consists of a glass tube (fig. 382), bevelled at its two extremities, and closed by glass plates, which are at an angle of 143°. This tube is connected with a bell-jar, H, in which there is a siphon barometer, and with a stopcock by means of which the apparatus can be exhausted, and different gases introduced. After having exhausted the tube AB, a ray of light, SA, is transmitted, which is bent away from the normal through an angle $r-i$ at the first incidence, and towards it through an angle $i'-r'$ at the second. These two deviations being added, the total deviation d is $r-i+i'-r'$. In the case of a minimum deviation, $i=r'$ and $r=i'$, whence $d=A-2i$, since $r+i'=A$ (492). The index from vacuum to air, which is evidently $\frac{\sin r}{\sin i}$, has therefore the value

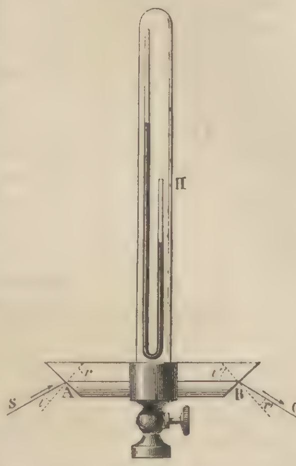


Fig. 382.

$$\frac{\sin\frac{A}{2}}{\sin\left(\frac{A-d}{2}\right)} \quad \cdot \quad \cdot \quad \cdot \quad (4)$$

Hence, in order to deduce the refractive index from vacuum into air, which is the *absolute index*, or *principal index*, it is simply necessary to know the refracting angle A, and the angle of minimum deviation d.

To obtain the absolute index of any other gas, after having produced a vacuum, this gas is introduced; the angles A and d having been measured, the above formula gives the index of refraction from gas to air. Dividing the index of refraction from vacuum to air by the index of refraction from the gas to air, we obtain the index of refraction from vacuum to the gas, that is, its absolute index.

By means of this apparatus Biot and Arago have found that the refractive indices of gases are very small as compared with those of solids and liquids, and that for the same gas the *refractive power* is proportional to the density; meaning by the refractive action of a substance the square of its refractive index less unity; that is, n^2-1. The refractive action divided by the density, or

$$\frac{n^2-1}{d},$$

is called the *absolute refractive power*.

Table of the absolute indices of refraction.

Diamond . . .	2·47 to 2·75	Sulphur	2·115
Phosphorus . . .	2·224	Ruby	1·779

Bisulphide of carbon	1·678	Turpentine	1·470
Iceland spar, ordinary ray	1·654	Alcohol	1·374
Iceland spar, extraordinary ray	1·483	Albumen	1·360
Flint glass	1·575	Ether	1·358
Rock salt	1·550	Crystalline lens	1·384
„ crystal	1·548	Vitreous „	1·339
Plate glass, St. Gobin	1·543	Aqueous „	1·337
Crown glass	1·500	Water	1·336
		Ice	1·310

Refractive indices of gases.

Vacuum	1·000000	Carbonic acid	1·000449
Hydrogen	1·000138	Hydrochloric acid	1·000449
Oxygen	1·000272	Nitrous oxide	1·000503
Air	1·000294	Sulphurous acid	1·000665
Nitrogen	1·000300	Olefiant gas	1·000678
Ammonia	1·000385	Chlorine	1·000772

LENSES. THEIR EFFECTS.

497. **Different kinds of lenses.**—*Lenses* are transparent media, which, from the curvature of their surfaces, have the property of causing the luminous rays which traverse them either to converge or to diverge. According to their curvature they are either spherical, cylindrical, elliptical, or parabolic. Those used in optics are always spherical. They are commonly made either of *crown glass*, which is free from lead, or of *flint glass*, which contains lead, and is more refractive than crown glass.

The combination of spherical surfaces, either with each other or with plane surfaces, gives rise to six kinds of lenses, sections of which are

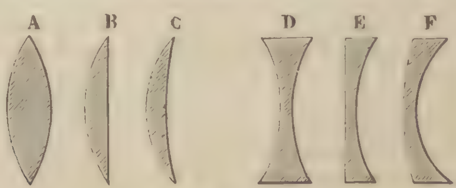


Fig. 383.

represented in fig. 383; four are formed by two spherical surfaces, and two by a plane and a spherical surface.

A is a *double convex*, B is a *plano-convex*, C is a *converging concavo-convex*, D is a *double concave*, E is a *plano-concave*, and F is a *diverging concavo-convex*. The lens C is also called the *converging meniscus*, and the lens F the *diverging meniscus*.

The first three, which are thicker at the centre than at the borders, are *converging*; the others, which are thinner in the centre, are *diverging*. In the first group, the double convex lens only need be considered, and

in the second the double concave, as the properties of each of these lenses apply to all those of the same group.

In lenses whose two surfaces are spherical, the centres for these surfaces are called *centres of curvature*, and the right line which passes through these two centres is the *principal axis*. In a plano-concave or plano-convex lens, the principal axis is the perpendicular let fall from the centre of the spherical face on the plane face.

In order to compare the path of a luminous ray in a lens with that in a prism, the same hypothesis is made as for curved mirrors (472), that is, the surfaces of these lenses are supposed to be formed of an infinity of small plane surfaces or elements; the *normal* at any point is then the perpendicular to the plane of the corresponding element. It is a geometrical principle that all the normals to the same spherical surface pass through its centre. On the above hypothesis we can always conceive two plane surfaces at the points of incidence and convergence, which are inclined to each other, and thus produce the effect of a prism. Pursuing this comparison, the three lenses A, B, and C may be compared to a succession of prisms having their summits outwards, and the lenses D, E, and F to a series having their summits inwards; from this we see that the first ought to condense the rays, and the latter to disperse them, for we have already seen that when a luminous ray traverses a prism it is deflected towards the base (491).

498. **Foci in double convex lenses.**—The focus of a lens is the point where the refracted rays, or their prolongations, meet. Double convex lenses have the same kind of foci as concave mirrors; that is, real foci and virtual foci.

Real foci. We shall first consider the case in which the luminous rays which fall on the lens are parallel to its principal axis, as shown in the fig. 384. In this case, any incident ray, LB, in approaching the normal

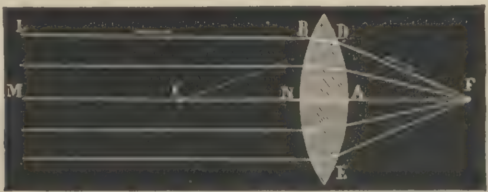


Fig. 384.

of the point of incidence B, and in diverging from it at the point of emergence D, is quite refracted towards the axis, which it cuts at F. As all rays parallel to the axis are refracted in the same manner, it can be shown by calculation that they all pass very nearly through the point F, so long as the arc DE does not exceed 10° to 12°. This point is called the *principal focus*, and the distance FA is the *principal focal distance.* It is constant in the same lens, but varies with the radii of curvature and the index of refraction. In ordinary lenses, which are of crown glass, and in

which the radii of the two surfaces are nearly equal, the principal focus coincides very closely with the centre of curvature.

We shall now consider the case in which the luminous object is outside the principal focus, but so near that all incident rays form a divergent pencil, as shown in fig. 385. The luminous point being at L, by comparing

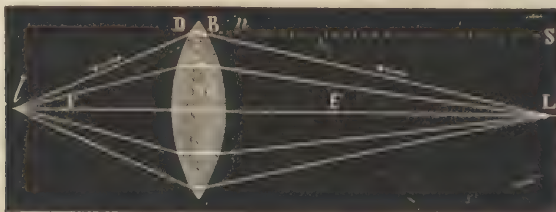


Fig. 385.

the path of a diverging ray, LB, with that of a ray, SB, parallel to the axis, the former is found to make with the normal an angle, LB*n*, greater than the angle SB*n*; consequently, after traversing the lens, the ray cuts the axis at a point, *l*, which is more distant than the principal focus F. As all rays from the point L intersect approximately in the same point *l*, this latter is the *conjugate focus* of the point L; this term has the same meaning here as in the cases of mirrors, and expresses the relation existing between the two points L and *l*, which is of such a nature, that if the luminous point is moved to *l*, the focus passes to L.

According as the object comes near the lenses, the convergence of the emergent rays decreases, and the focus *l* becomes more distant; when the object L coincides with the principal focus, the emergent rays on the other side are parallel to the axis, and there is no focus, or, what is the same thing, it is infinitely distant. As the refracted rays are parallel in this case, the intensity of light only decreases slowly, and a simple lamp can illuminate great distances. It is merely necessary to place it in the focus of a double concave lens, as shown in fig. 386.

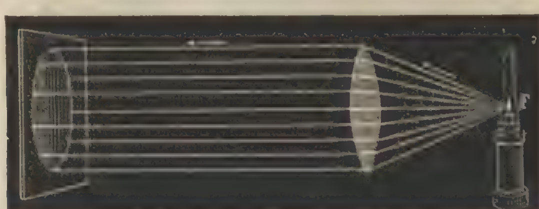


Fig. 386.

Virtual foci. A double convex lens has a virtual focus when the luminous object is placed between the lens and the principal focus, as shown in fig. 387. In this case the incident rays make with the normal greater angles than those made by the rays FI from the principal focus;

hence, when the former rays emerge, they move farther from the axis than the latter, and form a diverging pencil, HK, GM. These rays

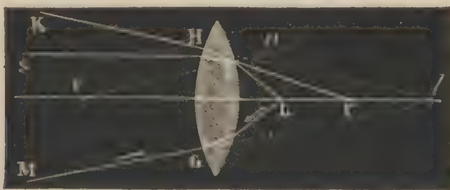


Fig. 387.

cannot produce a real focus, but their prolongations intersect in some point, *l*, on the axis, and this point is the virtual focus of the point L (466).

499. **Foci in double concave lenses.**—In double concave lenses there are only virtual foci, whatever the distance of the object. Let SI be any pencil of rays parallel to the axis (fig. 388), any ray, SI, is refracted at the

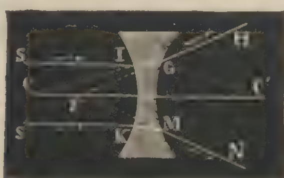


Fig. 388.

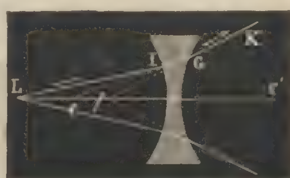


Fig. 389.

point of incidence I, and approaches the normal CI. At the point of emergence it is refracted, but diverges from the normal GC′, so that it is twice refracted in a direction which moves it from the axis CC′. As the same thing takes place for every other ray, S′KMN, it follows that the rays, after traversing the lens, form a diverging pencil, GH, MN. Hence there is no real focus, but the prolongations of these rays cut one another in a point, F, which is the principal virtual focus.

In the case in which the rays proceed from a point, L (fig. 390), on the axis, it is found by the same construction that a virtual focus is formed at *l*, which is between the principal focus and the lens.

500. **Experimental determination of the principal focus of lenses.**—To determine the principal focus of a double convex lens, it may be exposed to the sun's rays so that they are parallel to its axis. The emergent pencil being received on a ground glass screen, the point to which the rays converge is readily seen; it is the principal focus.

With a double concave lens, the face *ab* (fig. 391) is covered with an opaque substance, such as lampblack, two small apertures, *a* and *b*, being left in the same principal section, and at an equal distance from the axis; a pencil of solar light is then received on the other face, and the screen P, which receives the emergent rays, is moved nearer to or farther from the

lens, until A and B, the spots of light from the small apertures *a* and *b*, are distant from each other by twice *ab*. The distance DI is then equal

Fig. 390.

to the focal distance FD, because the triangles F*ab* and FAB are similar.

501. **Optical centre, secondary axis.**—In every lens there is a point called the *optical centre*, which is situated on the axis, and which has the property that any luminous ray passing through it experiences no angular deviation; that is, that the emergent ray is parallel to the incident ray. The existence of this point may be demonstrated in the following manner: Let two parallel radii of curvature, CA and C′A′ (fig. 391) be drawn to

Fig. 391.

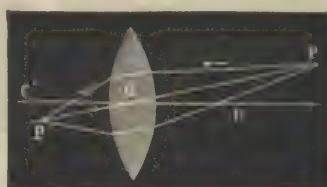


Fig. 392.

the two surfaces of a double convex lens. Since the two plane elements of the lens A and A′ are parallel, as being perpendicular to two parallel right lines, it will be granted that the refracted ray KA, A′K′ is propagated in a medium with parallel faces. Hence, a ray which reaches A at such an inclination, that after refraction it takes the direction AA′, will emerge parallel to its first direction (489); the point O, at which the right line cuts the axis, is therefore the optical centre. The position of this point may be determined for the case in which the curvature of the two faces is the same, which is the usual condition, by observing that the triangles COA and C′OA′ are equal, and therefore that OC = OC′, which gives the point O. If the curvatures are unequal, the triangles COA and C′OA′ are similar, and either CO or C′O may be found, and therefore also the point O.

In double concave or concavo-convex lenses the optical centre may be determined by the same construction. In lenses with a plane face this point is at the intersection of the axis by the curved face.

Every right line, PP′ (fig. 392), which passes through the optical centre without passing through the centres of curvature, is a *secondary axis*.

From the property of the optical centre, every secondary axis represents a luminous rectilinear ray passing through this point, for from the slight thickness of the lenses, it may be assumed that rays passing through the optical centre are in a right line ; that is, that the small deviation may be neglected which rays experience in traversing a medium with parallel faces (fig. 378).

So long as the secondary axes only make a small angle with the principal axis, all that has hitherto been said about the principal axis is applicable to them ; that is, that rays emitted from a point, P (fig. 392), on the secondary axis PP′, nearly converge to a certain point of this axis, P′, and according as the distance from the point P to the lens is greater or less than the principal focal distance, the focus thus formed will be conjugate or virtual. This principle is the foundation of what follows as to the formation of images.

502. **Formation of images in double convex lenses.**—In lenses as well as in mirrors the image of an object is the collection of the foci of its several points ; hence the images furnished by lenses are real or virtual in the same case as the foci, and their construction resolves itself into determining a series of points, as was the case with mirrors (475).

i. *Real image.* Let AB (fig. 393) be placed beyond the principal focus. If a secondary axis, A*a*, be drawn from the outside point A, any ray, AC,

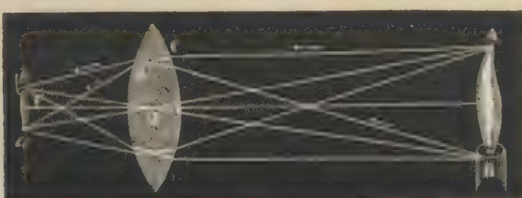


Fig. 393.

from this point, will be twice refracted at C and D, and both times in the same direction, approaching the secondary axis, which it cuts at *a*. From what has been said in the last paragraph, the other rays from the point A will intersect in the point *a*, which is accordingly the conjugate focus of the point A. If the secondary axis be drawn from the point B, it will be seen, in like manner, that the rays from this point intersect in the point *b*, and as the points between A and B have their foci between *a* and *b*, a *real* but *inverted* image of AB will be formed at *ab*.

In order to see this image, it may be received on a white screen, on which it will be depicted, or the eye may be placed in the path of the rays emerging from it.

Conversely, if *ab* were the luminous or illuminated object which emitted rays, its image would be formed at AB. Two consequences important for the theory of optical instruments follow from this : that, 1st, *If an object, even a very large one, is at a sufficient distance from a double convex lens, the real and inverted image which is obtained of it is*

very small, it is near the principal focus, but somewhat farther from the lens than this is; 2nd, *If a very small object be placed near the principal focus, but a little before it, the image which is formed is at a great distance, it is much larger, and that in proportion as the object is nearer the principal focus.* In all cases the object and the image have the same proportion as their distances from the lens.

These two principles are experimentally confirmed by receiving on a screen the image of a lighted candle, placed successively at various distances from a double convex lens.

ii. *Virtual image.* There is another case in which the object AB (fig. 394) is placed between the lens and its principal focus. If a secondary axis, O*a*,

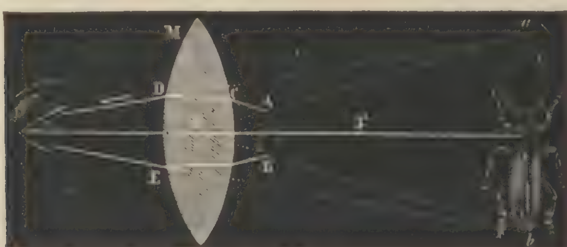


Fig. 394.

be drawn from the point A, every ray, AC, after having been twice refracted on emerging, diverges from this axis, since the point A is at a less distance than the principal focal distance (498). This ray, continued in an opposite direction, will cut the axis O*a* in the point *a*, which is the virtual focus of the point A. Tracing the secondary axis of the point B, it will be found, in the same manner, that the virtual focus of this point is formed at *b*. There is, therefore, an image of AB at *ab*. *This is a virtual image, it is erect, and larger than the object.*

The magnifying power is greater in proportion as the lens is more convex, and the object nearer the principal focus. We shall presently show how the magnifying power may be calculated by means of the formulæ relating to lenses (505). Double convex lenses, used in this manner as magnifying glasses, are called *simple microscopes.*

503. **Formation of images in double concave lenses.**—Double concave lenses, like convex mirrors, only give virtual images, whatever the distance of the object.

Let AB (fig. 395) be an object placed in front of such a lens. If the secondary axis be drawn from the point A, all rays, AC, AI, from this point are twice refracted in the same direction, diverging from the axis AO; so that the eye, receiving the emergent rays DE and GH, supposes them to proceed from the point where their prolongations cut the secondary axis AO in the point *a*. In like manner, drawing a secondary axis from the point B, the rays from this point form a pencil of divergent rays, the directions of which, prolonged, intersect in *b*. Hence the eye

sees at *ab* a virtual image of AB, *which is always erect, and smaller than the object.*

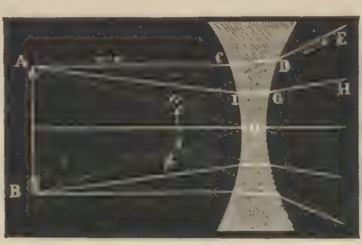


Fig. 395.

504. **Spherical aberration. Caustics.**—In the theory of the foci, and of the images formed by different kinds of spherical lenses, it has been hitherto assumed, that the rays emitted from a single point intersect also after refraction in a single point. This is virtually the case with a lens whose aperture—that is, the angle obtained by joining the edges to the principal focus—does not exceed 10° or 12°.

Where the aperture is larger, the rays which traverse the lens near the edge are refracted to a point nearer the lens than the rays which pass near the axis. The phenomenon thus produced is named *spherical aberration by refraction*; it is analogous to the spherical aberration produced by reflection. The luminous surfaces formed by the intersection of the refracted rays are termed *caustics by refraction.*

Spherical aberration is prejudicial to the sharpness and definition of an image. If a ground glass screen be placed exactly in the focus of a lens, the image of an object will be sharply defined in the centre, but indistinct at the edges; and, *vice versâ*, if the image is sharp at the edges, it will be indistinct in the centre. This defect is very objectionable, more especially in lenses used for photography. It is partially obviated by placing before the lenses diaphragms provided with a central aperture, which admits the

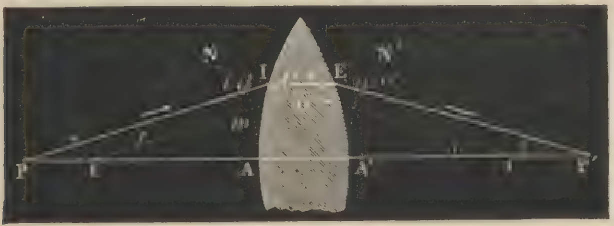


Fig. 396.

rays passing near the centre, but cuts off those which pass near the edges. Also by combining two lenses of suitable curvature, the spherical aberration may be destroyed.

505. **Formulæ relating to lenses.**—In all lenses, the relation between

the distances of the image and object, the radii of curvature, and the refractive index, may be expressed by a formula. In the case of a double convex lens, let P be a luminous point, situate on the axis fig. 396, let PI be an incident ray, IE its direction within the lens, EP′ the emergent ray, so that P′ is the conjugate focus of P. Further, let C′I and CE be the normals to the points of incidence and emergence, and IPA be put equal to α, $EP'A'=\beta$, $ECA'=\gamma$, $IC'A=\delta$, $NIP=i$, $EIO=r$, $IEO=i'$, $N'EP'=r'$.

Because the angle i is the exterior angle of the triangle PIC′, and the angle r' the exterior angle of the triangle CEP′, therefore, $i=\alpha+\delta$, and $r'=\gamma+\beta$, whence

$$i+r'=\alpha+\beta+\gamma+\delta \quad . \quad . \quad . \quad . \quad (1)$$

But at the point I, $\sin i = n \sin r$, and at the point E, $\sin r' = n \sin i'$ (485), n being the refractive index of the lens. Now if the arc AI is only a small number of degrees, these sines may be considered as proportional to the angles i, r, i', and r, whence, in the above formula, we may replace the sines by their angles, which gives $i=nr$ and $r'=ni'$, from which $i+r'=n\ (r+i')$. Further, because the two triangles IOE and COC′ have a common equal angle, O, therefore $r+i'=\gamma+\delta$, from which $i+r'=n\ (\gamma+\delta)$. Introducing this value into the equation (1) we obtain

$$n\ (\gamma+\delta)=\alpha+\beta+\gamma+\delta, \text{ from which } (n-1)\ (\gamma+\delta)=\alpha+\beta \quad . \quad . \quad (2)$$

Let CA′ be denoted by R, C′A by R′, PA by p, and P′A′ by p'. Then with centre P and radius PA describe the arc Ad, and with centre P′ and radius P′A′ describe the arc An. Now when an angle at the centre of a circle subtends a certain arc of the circumference, the quotient of the arc divided by the radius measures the angle; consequently

$$\alpha=\frac{Ad}{PA} \text{ or } \frac{Ad}{p}, \beta=\frac{A'n}{p'}, \gamma=\frac{A'E}{R}, \text{ and } \delta=\frac{AI}{R'}.$$

Therefore by substitution in (2)

$$(n-1)\left(\frac{A'E}{R}+\frac{AI}{R'}\right)=\frac{Ad}{p}+\frac{A'n}{p'}.$$

Now since the thickness of the lens is very small, and the angles also small, Ad, AI, A′E, and A′n differ but little from coincident straight lines, and are therefore virtually equal. Hence the above equation becomes

$$(n-1)\left(\frac{1}{R}+\frac{1}{R'}\right)=\frac{1}{p}+\frac{1}{p'} \quad . \quad . \quad . \quad . \quad (3)$$

This is the formula for double convex lenses; if p be $=\infty$, we have

$$(n-1)\left(\frac{1}{R}+\frac{1}{R'}\right)=\frac{1}{p'}$$

p' being the principal focal distance. If this be represented by f, we get

$$(n-1)\left(\frac{1}{R}+\frac{1}{R'}\right)=\frac{1}{f} \quad . \quad . \quad . \quad . \quad (4)$$

from which the value of f is easily deduced. Considered in reference to formula (4), the formula (3) assumes the form

$$\frac{1}{p}+\frac{1}{p'}=\frac{1}{f} \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

which is that in which it is usually employed. When the image is virtual, p' changes its sign, and formula (5) takes the form

$$\frac{1}{p}-\frac{1}{p'}=\frac{1}{f} \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

In double concave lenses, p' and f retain the same sign, but that of p changes; the formula (5) becomes then

$$\frac{1}{p}-\frac{1}{p'}=-\frac{1}{f} \quad . \quad . \quad . \quad . \qquad (7)$$

The formula (7) may be obtained by the same reasonings as the other.

CHAPTER IV.

DISPERSION AND ACHROMATISM.

506. **Decomposition of white light. Solar spectrum.**—The phenomenon of refraction is by no means so simple as we have hitherto assumed; when *white* light, or that which reaches us from the sun, passes from one medium into another, *it is decomposed into several kinds of lights*, a phenomenon to which the name *dispersion* is given.

In order to show that white light is decomposed by refraction, a pencil of solar light, SA (fig. 397), is allowed to pass through a small aperture

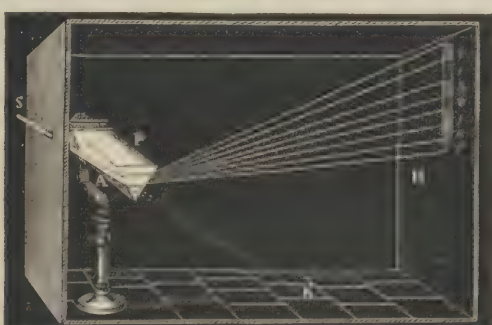


Fig. 397.

in the window shutter of a dark chamber. This pencil tends to form a round and colourless image of the sun at K; but if a flint glass prism, arranged horizontally, be interposed in its passage, the beam, on emerging from the prism, becomes refracted towards its base, and produces on a

distant screen a vertical band, coloured in all the tints of the rainbow, which is called the *solar spectrum.* In this spectrum there is, in reality, an infinity of different tints, which imperceptibly merge into each other, but it is customary to distinguish seven principal colours. These are *violet, indigo, blue, green, yellow, orange, red*; they are arranged in this order in the spectrum, the violet being the most refrangible, and the red the least so. They do not all occupy an equal extent in the spectrum, violet having the greatest extent, and orange the least.

With transparent prisms of different substances, or with hollow glass prisms filled with various liquids, spectra are obtained formed of the same colours, and in the same order; but when the deviation produced is the same, the length of the spectrum varies with the substance of which the prism is made. The angle of separation of two selected rays (say in the red and the violet) produced by a prism is called the dispersion, and the ratio of this angle to the mean deviation of the two rays is called the *dispersive power.* This ratio is constant for the same substance so long as the refracting angle of the prism is small. For the deviations of the two rays are proportional to the refracting angle; their

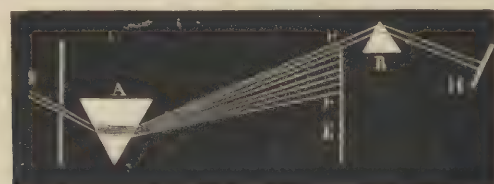


Fig. 398.

difference and their mean vary in the same manner, and, therefore, the ratio of their difference to their mean is constant. For flint glass this is 0·043; for crown glass it is 0·0246; for the dispersive power of flint is almost double that of crown glass.

The spectra which are formed by artificial lights rarely contain all the colours of the solar spectrum; but their colours are found in the solar spectrum, and in the same order. Their relative intensity is also modified. The shade of colour which predominates in the flame predominates also in the spectrum; yellow, red, and green flames produce spectra in which the dominant tint is yellow, red, or green.

In order to produce a solar spectrum in which the seven principal tints are distinctly seen, the aperture by which light enters ought not to be more than a few millimeters in diameter, and if the refracting angle of the prism, as is usually the case, is 60°, the screen on which the spectrum is caught must be 5 or 6 yards distant.

507. **The colours of the spectrum are simple, and unequally refrangible.**—If one of the colours of the spectrum be isolated by intercepting the others by means of a screen, E, as shown in fig. 398, and if the light thus intercepted be allowed to pass through a second prism, B, a refraction will be observed, but the light remains unchanged; that is,

the image received on the screen H is violet if the violet pencil has been allowed to pass, blue if the blue pencil, and so on. Hence the colours of the spectrum are *simple*; that is, they cannot further be decomposed by the prism.

Moreover, the colours of the spectrum are unequally refrangible; that is, they possess different refractive indices. The elongated shape of the spectrum would be sufficient to prove the unequal refrangibility of the simple colours, for it is clear that the violet, which is most deflected towards the base of the prism, is also most refrangible, and that red which is least deflected is least refrangible. But the unequal refrangibility of simple colours may be shown by numerous experiments, of which the two following may be adduced:

i. Two narrow strips of coloured paper, one red and the other violet, are fastened close to each other on a sheet of black paper. On looking at them through a prism, they are seen to be unequally displaced, the red band to a less extent than the violet; hence the red rays are less refrangible than the violet.

ii. The same conclusion may be drawn from Newton's experiment with crossed prisms. On a prism, A (fig. 399), in a horizontal position

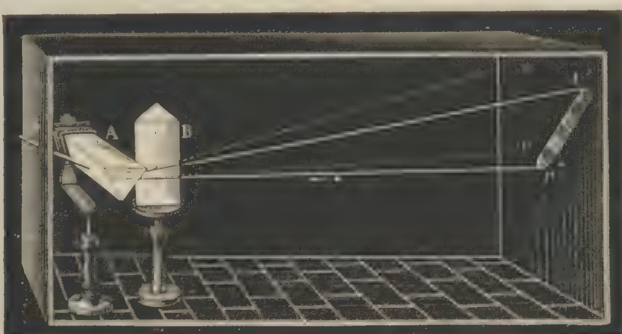


Fig. 399.

a pencil of white light, S, is received, which, if it had merely traversed the prism A, would form the spectrum rv, on a distant screen. But if a second prism, B, be placed in a vertical position behind the first, in such a manner that the refracted pencil passes through it, the spectrum vr becomes deflected towards the base of the vertical prism; but instead of being deflected in a direction parallel to itself, as would be the case if the colours of the spectrum were equally refracted, it is obliquely refracted in the direction $r'v'$, proving that from red to violet the colours are more and more refrangible.

These different experiments show that the refractive index differs in different colours; even rays which are to perception undistinguishable have not the same refractive index. In the red band, for instance, the rays at the extremity of the spectrum are less refracted than those which

are nearer the orange zone. In calculating indices of refraction (485), it is usual to take as the index of a substance the refrangibility of the yellow ray in a prism formed of that substance.

508. **Recomposition of white light.**—Not merely can white light be resolved into lights of various colours, but by combining the different pencils separated by the prism, white light can be reproduced. This may be effected in various ways :

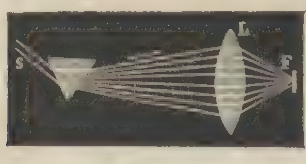


Fig. 400.

Fig. 401.

i. If the spectrum produced by one prism be allowed to fall upon a second prism of the same material, and the same refracting angle as the first, but inverted, as shown in fig. 401, the latter reunites the different colours of the spectrum, and it is seen that the emergent pencil E, which is parallel to the pencil S, is colourless.

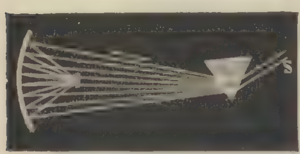


Fig. 402.

ii. If the spectrum falls upon a double convex lens (fig. 400), a white image of the sun will be formed on a white screen placed in the focus of the lens; a glass globe filled with water produces the same effect as the lens.

iii. When the spectrum falls upon a concave mirror, a white image is formed on a screen of ground glass placed in its focus (fig. 402).

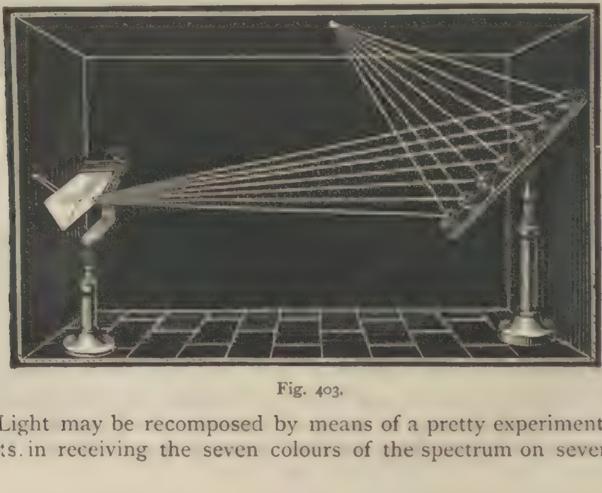


Fig. 403.

iv. Light may be recomposed by means of a pretty experiment, which consists in receiving the seven colours of the spectrum on seven small

glass mirrors with plane faces, and which can be so inclined in all positions that the reflected light may be transmitted in any given direction (fig. 403). When these mirrors are suitably arranged, the seven reflected pencils may be caused to fall on the ceiling in such a manner as to form seven distinct images—red, orange, yellow, etc. When the mirrors are moved so that the separate images become superposed, a single image is obtained, which is white.

v. By means of Newton's disc, it may be shown that the seven colours of the spectrum form white. This is a cardboard disc of about a foot in diameter ; the centre and the edges are covered with black paper, while in the space between there are pasted strips of papers of the colours of the spectrum. They proceed from the centre to the circumference, and their relative dimensions and tints are such as to represent five spectra (fig. 404). When this disc is rapidly rotated, the retina receives simultaneously the impression of the seven colours, and the disc appears white

Fig. 404.

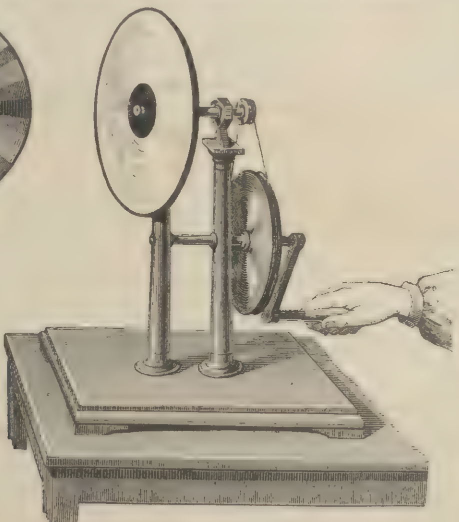


Fig. 405.

(fig. 405), or at all events of a greyish-white, for the colours which cover it cannot be arranged exactly in the same dimensions as those of the spectrum, nor can the colours be made of exactly the same tints.

509. **Newton's theory of the composition of light and the colour of bodies.**—Newton was the first to decompose white light by the prism, and to recompose it. From the various experiments which we have described, he concluded that white light was not homogeneous, but formed of seven lights unequally refrangible, which he called *simple* or *primitive* lights. It is owing to their difference in refrangibility that they become separated in traversing the prism.

On this theory bodies also decompose light by reflection, and their colour depends on their reflecting power for the different simple colours. Those which reflect all colours in the proportion in which they exist in the spectrum are white; those which reflect none are black. Between these two limits there are infinite tints, according to the greater or less extent to which bodies reflect some colours and absorb others. Hence bodies have no colours of themselves, but are coloured by the kind of light which they reflect. In fact, if in a dark room the same body is successively illuminated by each of the colours of the spectrum, the body has no special colour; it appears red, orange, green, etc., according to the position in which it is placed. The colour of bodies also varies with the nature of the light. This is the case with the light of gas, and of a candle in which yellow predominates, and which communicates this tint to the objects which it illuminates.

510. **Complementary colours.**—If in white light any colour be suppressed, a mixture of the remainder is called the *complementary colour*, for it is the colour needed to complete the sensation of white light. A mixture of blue and yellow produces a *green*, and, accordingly green is the complementary colour to red. In like manner a mixture of red and yellow produces *orange*, which is complementary to blue. Similarly indigo is the complementary colour to yellow, and yellowish green to violet.

511. **Homogeneous light.**—The light emitted from luminous bodies is never quite pure. In optical researches it is frequently of great importance to procure *homogeneous* or *monochromatic* light. Common salt in the flame of a Bunsen's lamp gives a yellow of great purity. For red light, ordinary light is transmitted through glass coloured with suboxide of copper, which absorbs nearly all the rays excepting the red. A very pure blue is obtained by transmitting ordinary light through a glass trough with parallel sides, containing an ammoniacal solution of sulphate of copper.

512. **Properties of the spectrum.**—Besides its luminous properties, the spectrum is found to produce calorific and chemical effects.

Luminous properties. It appears from the experiments of Fraunhofer and of Herschel, that the light in the yellow part of the spectrum has the greatest intensity, and that in the violet the least.

Calorific effects. It was long known that the various parts of the spectrum differed in their calorific effects. Leslie found that a thermometer placed in different parts of the spectrum indicated a higher temperature as it moved from violet towards red. Herschel fixed the maximum intensity of the heating effects just outside the red; Berard in the red itself. Seebeck showed that those different effects depend on the nature of a prism: with a prism of water the greatest calorific effect is produced in the yellow; with one of alcohol it is in the orange-yellow; and with a prism of crown glass it is in the middle of the red.

Melloni, by using prisms and lenses of rock salt, and by availing himself of the extreme delicacy of the thermo-electric apparatus, first made a complete investigation of the calorific properties of the thermal spec-

trum. This result led, as we have seen, to the confirmation and extension of Seebeck's observation.

Chemical properties. In numerous phenomena, light acts as a chemical agent. For instance, chloride of silver blackens under the influence of light, transparent phosphorus becomes opaque, vegetable colouring matters fade, hydrogen and chlorine gases, when mixed, combine slowly in diffused light, and with explosive violence when exposed to direct sunlight. The chemical action differs in different parts of the spectrum. Scheele found that when chloride of silver was placed in the violet, the action was more energetic than in any other part. Wollaston observed that the action extended beyond the violet, and concluded that, besides the visible rays, there are some invisible and more highly refrangible rays. These are the chemical or *actinic* rays.

There is a curious difference in the action of the different rays. Moser placed an engraving on an iodized silver plate, and exposed it to the light until an action had commenced, and then placed it under a violet glass in the sunlight. After a few minutes a picture was seen with great distinctness, while when placed under a red or yellow glass it required a very long time, and was very indistinct. When, however, the iodized silver plate was first exposed in a camera obscura to blue light for two minutes, and was then brought under a red or yellow glass, an image quickly appeared, but not when placed under a green glass. It appears as if there are vibrations of a certain velocity which could commence an action and that there are others which are devoid of the property of commencing, but can continue and complete an action when once set up. Becquerel, who discovered these properties in luminous rays, called the former *exciting rays*, and the latter *continuing* or *phosphorogenic rays.* The phosphorogenic rays, for instance, have the property of rendering certain objects self-luminous in the dark after they have been exposed for some time to the light. Becquerel found that the phosphorogenic spectrum extended from indigo to beyond the violet.

513. **Dark lines of the spectrum.**—The colours of the solar spectrum are not continuous. For several grades of refrangibility rays are wanting, and in consequence, throughout the whole extent of the spectrum, there are a great number of very narrow dark lines. To observe them, a pencil of solar rays is admitted into a darkened room, through a narrow slit. At a distance of three or four yards we look at this slit through a prism of flint glass, which must be very free from flaws, taking care to hold its edge parallel to the slit. We then observe a great number of very delicate dark lines parallel to the edge of the prism, and at very unequal intervals.

The existence of the dark lines was first observed by Wollaston in 1802; but Fraunhofer, a celebrated optician of Münich, first studied and gave a detailed description of them. Fraunhofer mapped the lines, and indicated the most marked of them by the letters A, *a*, B, C, D, E, *b*, F, G, H; they are therefore generally known as Fraunhofer's lines.

The dark line A (see fig. I. of the coloured plate), is at the extremity and B in the middle of the red ray; C, at the boundary of the red and

orange ray; D is in the orange ray; E, in the green; F, in the blue; G, in the indigo; H, in the violet. There are certain other noticeable dark lines, such as *a* in the red, and *b* in the green. In the case of solar light the positions of the dark lines are fixed and definite; on this account they are used for obtaining an exact determination of the refractive index (494) of each colour; for example, the refractive index of the blue ray is, strictly speaking, that of the dark line F. In the spectra of artificial lights, and of the stars, the relative positions of the dark lines are changed. In the electric light the dark lines are replaced by brilliant lines. In coloured flames, that is to say, flames in which certain chemical substances undergo evaporation, the dark lines are replaced by very brilliant lines of light, which differ for different substances. Lastly, of the dark lines, some are constant in position and distinctness, such are Fraunhofer's lines; but some of the lines only appear as the sun nears the horizon, and others are strengthened. They are also influenced by the state of the atmosphere. The fixed lines are due to the sun; the variable lines have been proved by Jannsen and Secchi to be due to the aqueous vapour in the air, and are called atmospheric or *telluric* lines.

Fraunhofer counted in the spectrum more than 600 dark lines, more or less distinct, distributed irregularly from the extreme red to the extreme violet ray. Brewster counted 2000. By causing the refracted rays to pass successively through several analysing prisms, not merely has the existence of 3000 dark lines been ascertained, but several which had been supposed single have been shown to be double.

514. **Applications of Fraunhofer's lines.**—Subsequently to Fraunhofer, several physicists studied the dark lines of the spectrum. In 1822 Sir J. Herschel remarked that by volatilising substances in a flame a very delicate means is afforded of detecting certain ingredients by the colours they impart to certain of the dark lines of the spectrum; and Fox Talbot in 1834 suggests optical analysis as probably the most delicate means of detecting minute portions of a substance. To Kirchhoff and Bunsen, however, is really due the merit of basing on the observation of the lines of the spectrum a method of analysis. They ascertained that the salts of the same metal, when introduced into a flame, always produce lines identical in colour and position, but different in colour, position, or number for different metals, and finally that an exceedingly small quantity of a metal suffices to disclose its existence. Hence has arisen a new method of analysis, known by the name of *spectral analysis*.

515. **Spectroscope.**—The name of spectroscope has been given to the apparatus employed by Kirchhoff and Bunsen for the study of the spectrum. One of the forms of this apparatus is represented in fig. 406. It is composed of three telescopes mounted on a common foot, and whose axes converge towards a prism, P, of flint-glass. The telescope A is the only one which can turn round the prism. It is fixed in any required position by a clamping screw, *n*. The screw-head, *m*, is used to shift the position of the eyepiece, so that a clear image of the spectrum may be obtained, or, in other words, to *focus* the eyepiece. The screw-head *n* is used to change the inclination of the axis.

To explain the use of the telescopes B and C, we must refer to fig. 407, which shows the passage of the light through the apparatus. The rays emitted by the flame G fall on the lens *a*, and are caused to converge

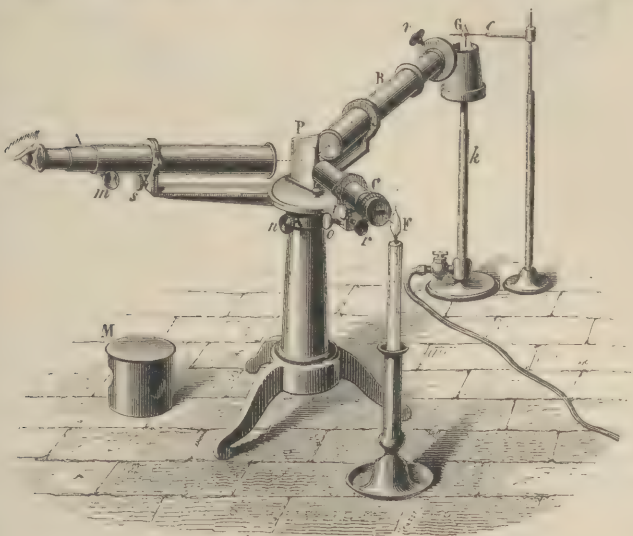


Fig. 406.

to a point, *b*, which is the principal focus of a second lens *c*. Consequently the pencil, on leaving the telescope B, is formed of parallel rays. This pencil enters the prism P. On leaving the prism, the light is decomposed, and in this state falls on the lens *x*. By the lens *x*, a real and reversed image of the spectrum is formed at *i*. This image is seen by the observer through a magnifying glass which forms at *ss'* a virtual image of the spectrum magnified about eight times.

The telescope C serves to measure the relative distances of the lines of the spectrum. For this purpose there is placed at *m* a micrometer divided into 25 equal parts. The micrometer is formed thus :—A scale of 250 millimeters is divided with great exactness into 25 equal parts. A photographic negative on glass of this scale is taken, reduced to 15 millimeters. The negative is taken because then the scale is light on a dark ground. The scale is then placed at *m* in the principal focus of the lens *e*; consequently, when the scale is lighted by the candle F, the rays emitted from it leave the lens *e* in parallel pencils; a portion of these, being reflected from a face of the prism, passes through the lens *x*, and forms a perfectly distinct image of the micrometer at *i*, thereby furnishing the means of measuring exactly the relative distances of the different spectral lines.

The micrometric telescope C (fig. 406) is furnished with several adjust-

ing screws, i, o, r : of these i adjusts the focus ; o displaces the micrometer in the direction of the spectrum laterally ; r raises or lowers

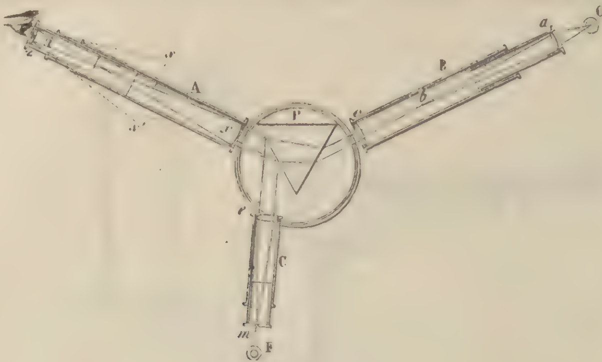


Fig. 407.

the micrometer, which it does by giving different inclinations to the telescope.

The opening whereby the light of the flame G enters the telescope B, consists of a narrow vertical slit, which can be opened more or less by causing the moveable piece a to advance or recede by means of the screw v (fig. 408). When for purposes of comparison two spectra are to be examined simultaneously, there is placed over the upper part of the slit a small prism whose refracting angle is 60°. Rays from one of the flames, H, fall at right angles on one face of the prism, they then experience total reflection on a second face, and leave the prism by the third face, and in a direction at right angles to that face. By this means they pass into the telescope in a direction parallel to its axis, without in any degree mixing with the rays which proceed from the second flame, G. Consequently the two pencils of rays traverse the prism P (fig. 407), and form two horizontal spectra which are viewed simultaneously through the telescope A. In the flames G and H are platinum wires, e, e'. These wires have been dipped beforehand into solutions of the salts of the metals on which experiment is to be made ; and by the vaporisation of these salts the metals modify the transmitted light, and give rise to definite lines.

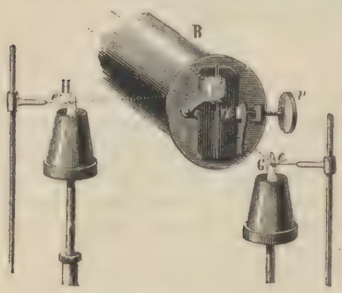


Fig. 408.

Each of the flames H and G is a jet of ordinary gas. The apparatus through which the gas is supplied is known as a *Bunsen's burner*. The gas comes through the hollow stem k (fig. 406). At the lower part of

this there is a lateral orifice to admit air to support the combustion of the gas. This orifice can be more or less closed by a small diaphragm which acts as a regulator. If we allow a moderate amount of air to enter, the gas burns with a luminous flame, and the lines are obscured. But if a strong and steady current of air enters, the carbon is rapidly oxidised, the flame loses its brightness, and burns with a pale blue light, but with an intense heat. In this state it no longer yields a spectrum. If, however, a metallic salt is introduced either in a solid state or in a state of solution, the spectrum of the metal makes its appearance, and in a fit state for observation.

There are three chief types of spectra; the *continuous* spectrum, or those furnished by ignited solids and liquids; the *band* or *line* spectrum, consisting of a number of bright lines, and produced by ignited gases or vapours; and *absorption* spectra, or those furnished by the sun or fixed stars. For an explanation of these see art. 517. Bodies at a red heat give only a small spectrum, extending at most to the orange; as the temperature gradually rises, yellow, green, blue, and violet successively appear, while the intensity of the lower colours increases.

516. **Experiments with the spectroscope.**—The coloured plate at the beginning shows certain spectra observed by means of the spectroscope. Fig. I. represents the solar spectrum.

Fig. II. shows the spectrum of potassium. It is *continuous*, that is, it contains all the colours of the solar spectrum; moreover, it is marked by two brilliant lines, one in the extreme red, corresponding to Fraunhofer's dark line A, the other in the extreme violet.

Fig. III. shows the spectrum of sodium. This spectrum contains neither red, orange, green, blue, nor violet. It is marked by a very brilliant yellow ray in exactly the same position as Fraunhofer's dark line D. Of all metals sodium is that which possesses the greatest spectral sensibility. In fact, it has been ascertained that one two hundred millionth of a grain of soda is enough to cause the appearance of the yellow line of sodium. Consequently it is very difficult to avoid the appearance of this line. A very little dust scattered in the apartment is enough to produce it,—a circumstance which shows how abundantly sodium is scattered throughout nature.

Figs. IV. and V. show the spectra of *cæsium* and *rubidium*, metals discovered by MM. Bunsen and Kirchhoff by means of spectral analysis. The former is distinguished by two blue lines, the latter by two very brilliant red lines and by two less intense violet lines. A third metal, *thallium*, has been discovered by the same method by Mr. Crookes in England, and independently by M. Lamy in France. Thallium is characterised by a single green line.

Still more recently Richter and Reich have discovered a new metal associated with zinc, and which they call *indium* from a couple of characteristic lines which it forms in the indigo.

The extreme delicacy of the spectrum reactions, and the ease with which they are produced, constitute them a most valuable help in the quantitative analysis of the alkalies and alkaline earths. It is sufficient to

place a small portion of the substance under examination on platinum wire as represented in fig. 408, and compare the spectrum thus obtained either directly with that of another substance, or with the charts in which the positions of the lines produced by the various metals are laid down.

With other metals the production of their spectrum is more difficult, especially in the case of some of their compounds. The heat of a Bunsen's burner is insufficient to vaporise the metals, and a more intense temperature must be used. This is effected by taking electric sparks between wires consisting of the metal whose spectrum is required, and the electric sparks are most conveniently obtained by means of Ruhmkorff's coil. Thus all the metals may be brought within the sphere of spectrum observations.

The power of the apparatus has great influence on the nature of the spectrum; while an apparatus with one prism only gives in a sodium flame the well-known yellow line, an apparatus with more prisms resolves it into two or three lines.

It has been observed that the character of the spectrum changes with the temperature; thus chloride of lithium in the flame of a Bunsen's burner gives a single intense peach-coloured line; in a hotter flame, as that of hydrogen, it gives an additional orange line; while in the oxy-hydrogen jet or the voltaic arc a broad brilliant blue band comes out in addition. The sodium spectrum produced by a Bunsen's burner consists of a single yellow line; if, by the addition of oxygen, the heat be gradually increased, more bright lines appear; and with the aid of the oxy-hydrogen flame the spectrum is continuous. Sometimes also, in addition to the appearance of new lines, an increase in temperature resolves those *bands* which exist into a number of fine *lines*, which in some cases are more and in some less refrangible than the bands from which they are formed. It may be supposed that the glowing vapour found at the low temperature consists of the oxide or some difficultly reducible metal, whereas at the enormously high temperature of the spark these compounds are decomposed, and the true bright lines of the spectrum are formed.

The delicacy of the reaction increases very considerably with the temperature. With the exception of the alkalies, it is from 40 to 300 times greater at the temperature of the electric spark than at that of Bunsen's burner.

The spectra of the gases are obtained by taking the electric spark of a Ruhmkorff's coil, or Holtz's apparatus, through glass tubes of a special construction, provided with electrodes of platinum and filled with the gas in question in a state of great attenuation; if the spark be passed through hydrogen, the light emitted is bright red, and its spectrum consists of one bright red, one green, and one blue line; whilst in nitrogen the spark is purple and the spectrum very complicated. If the electric discharge takes place through a compound gas or vapour, the spectra are those of the elementary constituents of the gas. It seems as if at very intense temperatures chemical combination was impossible, and oxygen and hydrogen, chlorine and the metals, could coexist in a separate form, although mechanically mixed with each other.

The nature of the spectra of the elementary gases is very materially influenced by alterations of temperature and pressure. Wüllner made a series of very accurate observations on the gases oxygen, hydrogen, and nitrogen. He not only used gases in closed tubes, which by various electrical means he raised to different temperatures; but in one and the same series of experiments, in which a small inductorium was used, he employed temperatures varying from 100 millimeters to a fraction of a millimeter; while in another series, in which a larger apparatus was used, he extended the pressure to 2,000 millimeters. At the lowest pressure of less than 1 millimeter, the spectrum of hydrogen was found to be green, and consisting of six splendid groups of lines, which at a higher pressure than 1 millimeter changed to continuous bands; at 2 to 3 millimeters the spectrum consisted of the often-mentioned three lines, which did not disappear under a higher pressure, but gradually became less brilliant as the continuous spectrum increased in extent and lustre. From this point the light, and therefore the spectrum, became feebler. Using the larger apparatus, the band spectrum appeared only under a higher pressure; at the highest pressure of 2,000 millimeters it gave place to the continuous spectrum, since the bright lines continually extended and ultimately merged into each other.

517. **Explanation of the dark lines of the solar spectrum.**—It has been already seen that incandescent sodium vapour gives a bright yellow line corresponding to the dark line D of the solar spectrum. Kirchhoff found that, when the brilliant light produced by incandescent lime passes through a flame coloured by sodium in the usual manner, a spectrum is produced in which is a dark line coinciding with the dark line D of the solar spectrum; what would have been a bright yellow line becomes a dark line when formed on the background of the lime light. By allowing in a similar manner the lime light to traverse vapours of potassium, barium, strontium, etc., the bright lines which they would have formed were found to be converted into dark lines, such spectra are called absorption spectra.

It appears then that the vapour of sodium has the power of absorbing rays of the same refrangibility as that which it emits. And the same is true of the vapours of potassium, barium, strontium, etc. This absorptive power is by no means an isolated phenomenon. These substances share it, for example, with the vapour of nitrous acid, which Brewster found to possess the following property: when a tube filled with this vapour is placed in the path of the light either of the sun or of a gas flame, and the light is subsequently decomposed by a prism, a spectrum is produced which is full of dark lines; and Miller showed that iodine and bromine vapour produced analogous effects.

Hence the origin of the above phenomenon is, doubtless, the absorption by the sodium vapour of rays of the same kind, that is, of the same refrangibility, as those which it has itself the power of emitting. Other rays it allows to pass unchanged, but these it either totally or in great part suppresses. Thus the particular lines in the spectrum to which these rays would converge are illuminated only by the feebly luminous sodium

flame, and accordingly appear dark by contrast with the other portions of the spectrum which receive light from the powerful flame behind.

By replacing one of the flames, G or H (fig. 408), by a ray of solar light reflected from a heliostat, Kirchhoff ascertained by direct comparison that the bright lines which characterise iron correspond to dark lines in the solar spectrum. He also found the same to be the case with sodium, magnesium, calcium, nickel, and some other metals.

From these observations we may draw important conclusions with respect to the constitution of the sun. Since the solar spectrum has dark lines where sodium, iron, etc., give bright ones, it is probable that around the solid, or more probably liquid, body of the sun, which throws out the light, there exists a vaporous envelope which, like the sodium flame in the experiment described above, absorbs certain rays, namely, those which the envelope itself emits. Hence those parts of the spectrum which, but for this absorption, would have been illuminated by these particular rays, appear feebly luminous in comparison with the other parts, since they are illuminated only by the light emitted by the envelope, and not by the solar nucleus; and we are at the same time led to conclude that in this vapour there exists the metals sodium, iron, etc.

Huggins and Miller have applied spectrum analysis to the investigation of the heavenly bodies. The spectra of the moon and planets, whose light is reflected from the sun, give the same lines as those of the sun. Uranus proves an exception to this, and is probably still in a self-luminous condition. The spectra of the fixed stars contain, however, dark lines differing from the solar lines, and from one another. The red star Aldebaran gave lines corresponding with sodium, magnesium, calcium, iron, bismuth, tellurium, antimony, and mercury. In the spectrum of the orange tinted star α Orionis the lines of magnesium, sodium, calcium, and bismuth, were observed. The brilliant white star Sirius gave evidence of the presence of sodium, magnesium, hydrogen, and iron. It would thus appear that these fixed stars, while differing from one another in the matter of which they are composed, are constructed on the same general plan as our sun. Huggins has observed a striking difference in the spectra of the nebulæ; where they can at all be observed, they are found to consist generally of bright lines, like the spectra of the ignited gases, instead of like the spectra of the sun and stars consisting of a bright ground intersected by dark lines. It is hence probable that the nebulæ are masses of glowing gas, and do not consist, like the sun and stars, of a photosphere surrounded by a gaseous atmosphere.

One of the most interesting triumphs of spectrum analysis has been the discovery of the true nature of the *protuberances*, which appear during a solar eclipse as mountains or cloud-shaped luminous objects varying in size, and surrounding the moon's disc.

During the eclipse of 1868 it had been ascertained by Jannsen that they emitted certain bright lines coinciding with those of hydrogen. They have, however, been fully understood only since Lockyer and Jannsen have discovered a method of investigating them at any time. The principle of this method is as follows. When a line of light admitted through

a slit is decomposed by a prism, the length of this spectrum may be increased by passing it through two or more prisms: as the quantity of light is the same, it is clear that the intensity of the spectrum will be diminished. This is the case with the ordinary sources of light, such as the sun; if the light be homogeneous, it will be merely deviated, and not reduced in intensity by dispersion. And if the source of light emit lights of both kinds, the image of the slit of light of a definite refrangibility which the mixture may contain will stand out by their superior intensity on the weaker ground of the continuous spectrum. This is the case with the spectrum of the protuberances. Viewed through an ordinary spectroscope, the light they emit is overshadowed by that of the sun; but by using prisms of great dispersive power the sun's light becomes weakened, and the spectrum of the protuberances may be obscured. Lockyer's researches leave no doubt that they are ignited gas masses, principally of hydrogen. By altering the position of the slit a series of sections of the prominences are obtained by collating which the form of the prominence may be inferred. They are thus found to enclose the sun usually to a depth of about 5,000 miles, but sometimes in enormous local accumulations, which reach the height of 70,000 miles. Lockyer has not merely examined these phenomena right on the edge of the sun; but he has been able to observe them on the disc itself. He has shown that some of these protuberances are the results of sudden outbursts or storms, which move with the enormous velocity of 120 miles in a second. N.B.—For a fuller account of this branch of Physics, which is incompatible with the limits of this work, the reader is referred to Roscoe's 'Lectures on Spectrum Analysis,' or to Schellen's 'Spectrum Analysis,' translated by Lassell.

518. **Uses of the spectroscope.**—When a liquid placed in a glass tube or in a suitable glass cell is interposed between a source of light and the slit of the spectroscope, on looking through the telescope, the spectrum observed will in many cases be found to be traversed by dark bands. As these bands differ in different liquids as regards position, breadth, and intensity, in many cases they afford the most suitable means of identifying bodies. Sorby and Browning have devised a combination of the microscope and spectroscope, called the *microspectroscope*, which renders it possible to examine even very minute traces of substances.

This application of the spectroscope has been very useful in investigating substances which have special importance in physiology and pathology; thus in examining normal and diseased blood, in detecting albumen in urine, and in ascertaining the rate at which certain substances pass into the various fluids of the system. The characteristic absorption bands which certain liquids, such as wine, beer, etc., present in their normal state, compared with those yielded by adulterated substances, furnishes a delicate and certain means of detecting the latter.

519. **Fluorescence.**—Professor Stokes has made the remarkable discovery that under certain circumstances the rays of light are capable of undergoing a change of refrangibility. The discovery originated in the study of a phenomenon observed by Sir J. Herschel, that certain solutions when looked at by transmitted light appear colourless, but when viewed

in reflected light present a bluish appearance. Stokes has found that this property, which he calls *fluorescence*, is characteristic of a large class of bodies.

The phenomenon is best seen when a solution of sulphate of quinine, contained in a trough with parallel sides, is placed in different positions in the solar spectrum. No change is observed in the upper part of the spectrum, but from about the middle of the lines G and H (frontispiece) to some distance beyond the extreme range of the violet, rays of a beautiful sky-blue colour are seen to proceed. These invisible ultra-violet rays also become visible when the spectrum is allowed to fall on paper impregnated with a solution of *æsculine* (a substance extracted from horse chestnut), an alcoholic solution of stramonium, or a plate of canary glass (which is coloured by means of uranium). This change arises from a diminution in the refrangibility of those rays outside the violet, which are ordinarily too refrangible to affect the eye.

Glass appears to absorb many of these more refrangible rays, which is not the case nearly to the same extent with quartz. When prisms and troughs formed of plates of quartz are used, a spectrum may be obtained which, outside the line H, is double the length of the visible spectrum. In the spectrum thus made visible dark lines may be seen like those in the ordinary spectrum.

The phenomena may be observed without the use of a prism. When an aperture in a dark room is closed by means of a piece of blue glass, and the light is allowed to fall upon a piece of canary glass, it instantly appears self-luminous from the emission of the altered rays.

In most cases it is the violet and ultra-violet rays which undergo an alteration of refrangibility, but the phenomenon is not confined to them. A decoction of madder in alum gives yellow and violet light from about the line D to beyond the violet; an alcoholic solution of chlorophylle gives red light from the line B to the limit of the spectrum. In these cases the yellow, the green, and the blue rays experience diminution of refrangibility; the change never produces more highly refrangible rays.

The electric light gives a very remarkable spectrum. With quartz apparatus Stokes obtained a spectrum six or eight times as long as the ordinary one. Several flames of no great illuminating power emit very peculiar light. Characters traced on paper with solution of stramonium, which are almost invisible in daylight, appear instantaneously when illuminated by the flame of burning sulphur. Robinson has found that the light of the aurora is peculiarly rich in rays of high refrangibility.

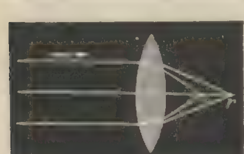


Fig. 409.

520. **Chromatic aberration.** — The various enses hitherto described (497) possess the inconvenience that, when at a certain distance from the eye, they give images with coloured edges. This defect, which is most observable in condensing lenses, is due to the unequal refrangibility of the simple colours (507), and is called *chromatic aberration.*

For, as a lens may be compared to a series of prisms with infinitely

small faces, and united at their bases, it not only refracts light, but also decomposes it like a prism. On account of this dispersion, therefore, lenses have really a distinct focus for each colour. In condensing lenses, for example, the red rays, which are the least refrangible, form their focus at a point, r, on the axis of the lens (fig. 409), while the violet rays, which are most refrangible, coincide in the nearest point, v. The foci of the orange, yellow, green, blue, and indigo are between these points. The chromatic aberration is more perceptible in proportion as the lenses are more convex, and as the point at which the rays are incident is further from the axis; for then the deviation, and therefore the dispersion are increased.

521. **Achromatism.**—By combining prisms which have different refracting angles (490), and are formed of substances of unequal dispersive powers (506), white light may be refracted without being dispersed. The same result is attained by combining lenses of different substances, the curvatures of which are suitably combined. The images of objects viewed through such lenses do not appear coloured, and they are accordingly called *achromatic* lenses; *achromatism* being the term applied to the phenomenon of the refraction of light without decomposition.

By observing the phenomenon of the dispersion of colours in prisms of water, of oil of turpentine, and of crown glass, Newton was led to suppose that dispersion was proportional to refraction. He concluded that there could be no refraction without dispersion, and, therefore, that achromatism was impossible. Almost half a century elapsed before this was found to be incorrect. Hall, an English philosopher, in 1733, was the first to construct achromatic lenses, but he did not publish his discovery. It is to Dollond, an optician in London, that we owe the greatest improvement which has been made in optical instruments. He showed in 1757 that by combining two lenses, one a double convex crown glass lens, the other a concavo-convex lens of flint glass (fig. 410), a lens is obtained which is virtually achromatic.

To explain this result, let two prisms, BFC and CDF, be joined and turned in a contrary direction, as shown in fig. 411. Let us suppose, in

Fig. 410.

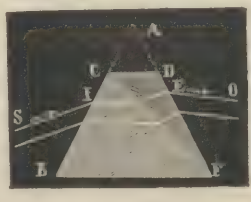


Fig. 411.

the first case, that both prisms are of the same material, but that the refracting angle of the second, CDF, is less than the refracting angle of the first; the two prisms will produce the same effect as a single prism, BAF; that is to say, that white light which traverses it will not only be refracted, but also decomposed. If, on the contrary, the first prism BCF

were of crown glass, and the other of flint glass, the dispersion might be destroyed without destroying the refraction. For as flint glass is more dispersive than crown, and as the dispersion produced by a prism diminishes with its refracting angle (506), it follows that by suitably lessening the refracting angle of the flint glass prism CFD, as compared with the refracting angle of the crown glass prism BCF, the dispersive power of these prisms may be equalised; and as, from their position, the dispersion takes place in a contrary direction, it is neutralised; that is, the emergent rays EO are parallel, and therefore give white light. Nevertheless, the ratio of the angles BCF and CFD, which is suitable for the parallelism of the red rays and violet rays, is not so for the intermediate rays, and, consequently, only two of the rays of the spectrum can be exactly combined, and the achromatism is not quite perfect. To obtain perfect achromatism, several prisms would be necessary, of unequally dispersive materials, and the angles of which were suitably combined.

The refraction is not destroyed at the same time as the dispersion; that could only happen if the refracting power of a body varied in the same ratio as its dispersive power, which is not the case. Consequently, the emergent ray EO is not exactly parallel to the incident ray, and there is a refraction without appreciable decomposition.

Achromatic lenses are made of two lenses of unequally dispersive materials: one, A, of flint glass, is a diverging concavo-convex (fig. 410); the other, B, of crown glass, is double convex, and one of its faces may exactly coincide with the concave face of the first. As with prisms, several lenses would be necessary to obtain perfect achromatism: but for optical instruments two are sufficient, their curvature being such as to combine the blue and orange rays.

CHAPTER V.

OPTICAL INSTRUMENTS.

522. **The different kinds of optical instruments.**—By the term *optical instrument* is meant any combination of lenses, or of lenses and mirrors. Optical instruments may be divided into three classes, according to the ends they are intended to answer, viz.:—i. *Microscopes*, which are designed to obtain a magnified image of any object whose real dimensions are too small to admit of its being seen distinctly by the naked eye. ii. *Telescopes*, by which very distant objects, whether celestial or terrestrial, may be observed. iii. *Instruments* designed to project on a screen a magnified or diminished image of any object which can thereby be either depicted or rendered visible to a crowd of spectators; such as the *camera lucida*, the *camera obscura*, *photographic apparatus*, the *magic lantern*, the *solar microscope*, the *photo-electric microscope*, etc. The two former classes yield virtual images; the last, with the exception of the *camera lucida*, yield real images.

MICROSCOPES.

523. **The simple microscope.**—The *simple microscope* or *magnifying glass* is merely a convex lens of short focal length, by means of which we look at objects placed between the lens and its principal focus. Let AB (fig. 412) be the object to be observed placed between the lens and its

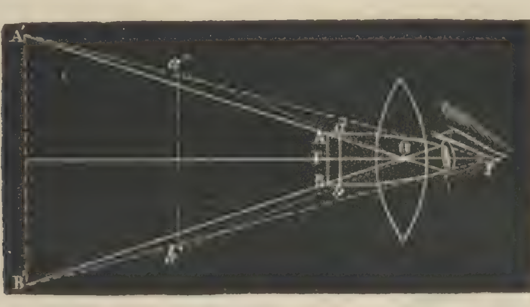


Fig. 412.

principal focus, F. Draw the secondary axes AO and BO, and also from A and B rays parallel to the axis of the lens FO. Now these rays, on passing out of the lens, tend to pass through the second principal focus F′, consequently they are divergent with reference to the secondary axes, and therefore, when produced, will cut those axes in A′ and B′ respectively. These points are the virtual foci of A and B respectively. The lens therefore produces at A′B′ an erect and magnified virtual image of the object AB.

The position and magnitude of this image depend on the distance of the object from the focus. Thus, if AB is moved to *ab* nearer the lens, the secondary axes will contain a greater angle, and the image will be formed at *a′b′*, and will be much smaller, and nearer the eye. On the other hand, if the object is moved farther from the lens, the angle between the secondary axes is diminished, and their intersection with the prolongation of the refracted rays taking place beyond A′B′, the image is formed farther from the lens, and is larger.

In a simple microscope both chromatic aberration and spherical

Fig. 413.

aberration increase with the degree of magnification. We have already seen that the former can be corrected by using achromatic lenses

(521), and the latter by using diaphragms which allow the passage of such rays only as are nearly parallel to the axis, the spherical aberration of these rays being nearly insensible. Spherical aberration may be still further corrected by using two plano-convex lenses instead of one very convergent lens. When this is done, the plane face of each lens is turned towards the object (fig. 413). Although each lens is less convex than the simple lens which they replace, yet their joint magnifying power is as great, and with a less amount of spherical aberration, since the first lens draws towards the axis the rays which fall on the second lens. This combination of lenses is known as *Wollaston's doublet.*

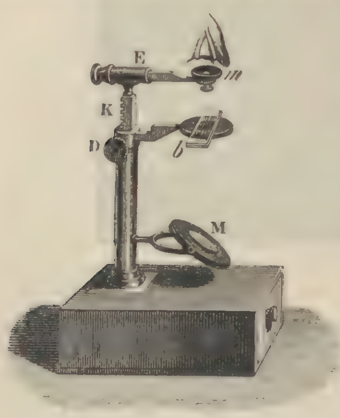


Fig. 414.

There are many forms of the simple microscope. One of the best is that represented in fig. 414. On a horizontal support, E, which can be raised and lowered by a rack and pinion, there is a black *eyepiece*, *m*, in the centre of which is fitted a small convex lens. Below this is the *stage*, which is fixed, and on which the object is placed between glass plates. In order to illuminate the object powerfully, diffused light is reflected from a concave glass mirror, M, so that the reflected rays fall upon the object. In using this microscope, the eye is placed very near the lens, which is lowered or raised until the position is found at which the object appears in its greatest distinctness.

524. **Conditions of distinctness of the images.**—In order that objects looked at through a microscope should be seen with distinctness they must have a strong light thrown upon them, but this is by no means enough. It is necessary that the image be formed at a determinate distance from the eye. In fact, there is for each person a *distance of most distinct vision*, a distance, that is to say, at which an object must be placed from an observer's eye, in order to be seen with greatest distinctness. This distance is different for different observers, but ordinarily is between 10 and 12 inches. It is, therefore, at this distance from the eye that the image ought to be formed. Moreover, this is why each observer has *to focus* the instrument, that is, to adapt the microscope to his own distance of most distinct vision. This is effected by slightly varying the distance from the lens to the object, for we have seen above that a slight displacement of the object causes a great displacement of the image. With a common magnifying glass, such as is held in the hand, the adjustment is effected by merely moving it nearer to or further from the object. In the microscope the adjustment is effected by means of a rack and pinion, which in the case of the instrument shown in fig. 414 moves the instrument, but moves the object in the case of the instrument

depicted in fig. 419. What has been said about *focussing* the microscope applies equally to telescopes. In the latter instruments the eyepiece is

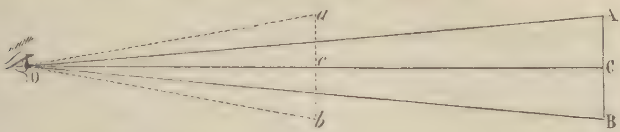


Fig. 416.

generally adjusted with respect to the image formed in the focus of the object glass.

525. **Apparent magnitude of an object.**—The apparent magnitude or apparent diameter of a body is the angle it subtends at the eye of the observer. Thus, if AB is the object, and O the observer's eye (figs. 415, 416), the apparent magnitude of the object is the angle AOB contained by two visual rays drawn from the centre of the pupil to the extremities of the object.

In the case of objects seen through optical instruments, the angles which they subtend are so small that the arcs which measure the angles do not differ sensibly from their tangents. The ratio of two such angles is therefore the same as that of their tangents. Hence we deduce the two following principles :—

I. *When the same object is seen at unequal distances, the apparent diameter varies inversely as the distance from the observer's eye.*

II. *In the case of two objects seen at the same distance, the ratio of the apparent diameters is the same as that of their absolute magnitudes.*

These principles may be proved as follows :—i. In fig. 415, let AB be the object in its first position, and *ab* the same object in its second position. For the sake of distinctness these are represented in such positions that the line OC passes at right angles through their middle points C and *c* respectively. It is, however, sufficient that *ab* and AB should be the bases of isosceles triangles having a common vertex at O. Now by what has been said above, AB is sensibly an arc of a circle described with centre O and radius OC ; likewise *ab* is sensibly an arc of a circle whose centre is O, and radius O*c*. Therefore

$$\mathrm{AOB} : a\mathrm{O}b = \frac{\mathrm{AB}}{\mathrm{OC}} : \frac{ab}{\mathrm{O}c} = \frac{1}{\mathrm{OC}} : \frac{1}{\mathrm{O}c}.$$

Therefore AOB varies inversely as OC.

ii. Let AB and A′B′ be two objects placed at the same perpendicular

distance, OC, from the eye, O, of the observer (fig. 416). Then they are sensibly arcs of a circle whose centre is O, and radius OC. Therefore

$$AOB : A'OB' = \frac{AB}{OC} : \frac{A'B'}{OC} = AB : A'B,$$

a proportion which expresses the second principle.

526. **Measure of magnification.**—In the simple microscope, the measure of the magnification produced is the ratio of the apparent diameter of the image to that of the object, both being at the distance of most distinct vision.* The same rule holds good for other microscopes. It is, however, important to obtain an expression for the magnification depending on data that are of easier determination.

In fig. 417 let AB be the object, and A′B′ its image formed at the distance of most distinct vision. Let *a′b′* be the projection of AB on A′B′.

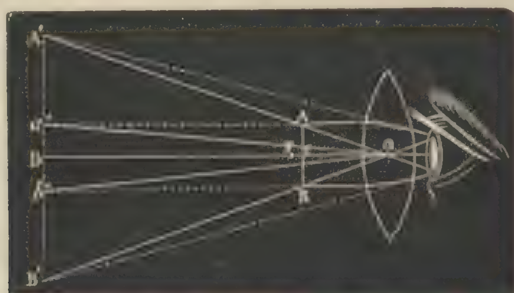


Fig. 417.

Then, since the eye is very near the glass, the magnification equals $\frac{A'OB'}{a'Ob'}$, or $\frac{A'B'}{a'b'}$, that is, $\frac{A'B'}{AB}$. But since the triangles A′OB′ and AOB are similar, A′B′ : AB = DO : CO. Now DO is the distance of most distinct vision, and CO is very nearly equal to FO, the focal length of the lens. Therefore the magnification equals the ratio of the distance of most distinct vision to the focal length of the lens. Hence we conclude that the magnification is greater:—1st, as the focal length of the lens is smaller, in other words, as the lens is more convergent; 2ndly, as the observer's distance of most distinct vision is greater.

By changing the lens the magnification can be increased, but only within certain limits if we wish to obtain a distinct image. By means of a simple microscope distinct magnification may be obtained up to 120 diameters.

The magnification we have now considered is *linear* magnification. *Superficial* magnification equals the square of the *linear* magnification; for instance, the former will be 1600 when the latter is 40.

* A simpler and more general definition may be stated thus:—Let α be the angular magnitude of the object as seen by the naked eye, β the angular magnitude of the image, whether real or virtual, actually present to the eye, then the magnification is $\beta \div \alpha$. This rule applies to telescopes.

527. **Compound microscope.**—The compound microscope in its simplest form consists of two condensing lenses : one with a short focus is called the *object glass* or *objective*, because it is turned towards the object; the other is less condensing, and is called the *eyepiece* or *power*, because it is close to the observer's eye.

Fig. 418 represents the path of the luminous rays, and the formation of the image in the simplest form of a compound microscope. An object,

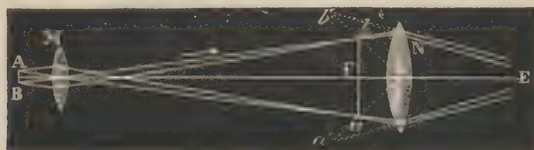


Fig. 418.

AB, being placed very near the principal focus of the object glass, M, but a little farther from the glass, a real image, *ab*, inverted and somewhat magnified, is formed on the other side of the object glass (502). Now the distance of the two lenses, M and N, is such that the position of the image, *ab*, is between the eyepiece N, and its focus, F. From this it follows that for the eye at E, looking at the image through the eyepiece, this glass produces the same effect as a simple microscope, and instead of this image, *ab*, another image, *a′b′*, is seen, which is virtual, and still more magnified. This second image, although erect as regards the first, is inverted in reference to the object. It may thus be said, that the compound microscope is nothing more than a simple microscope applied not to the object, but to its image already magnified by the first lens.

528. **Amici's compound microscope.**—The principle of the compound microscope has been already (527) explained; the principal accessories to the instrument remain to be described.

Fig. 419 represents the essential parts of the microscope known as *Amici's* or *Chevallier's* microscope. In the older microscopes the tube, A, was always vertical, and the lenses were not achromatic. Amici was the first to adopt an arrangement by which the tube could be placed either vertically or horizontally, and Chevallier was the first to introduce into France the use of achromatic lenses. The figure shows the microscope in a horizontal position, which is less fatiguing for the sight ; but it can also be placed vertically. This is effected by removing the tube G, and putting the long tube A, which contains the eyepiece, in its place over the object glass, E. The microscope may also be placed in an inclined position by removing a pin, *m*, which fixes the apparatus at the lower part ; the whole system then moves on a hinge, *a*, which supports the microscope on a cylindrical column.

On a rectangular rod, parallel to this column, is the *stage*, B. This can be raised or lowered by a pinion working in a rack by means of a milled head. The object, *o*, to be observed is placed on the stage between two pieces of glass, C. The diffused light of the atmosphere is reflected

through the object by means of a concave glass reflector, M ; the powerful illumination thus attained is indispensable with high magnifying powers. In the centre of the stage there is an aperture through which passes the light sent by the reflector.

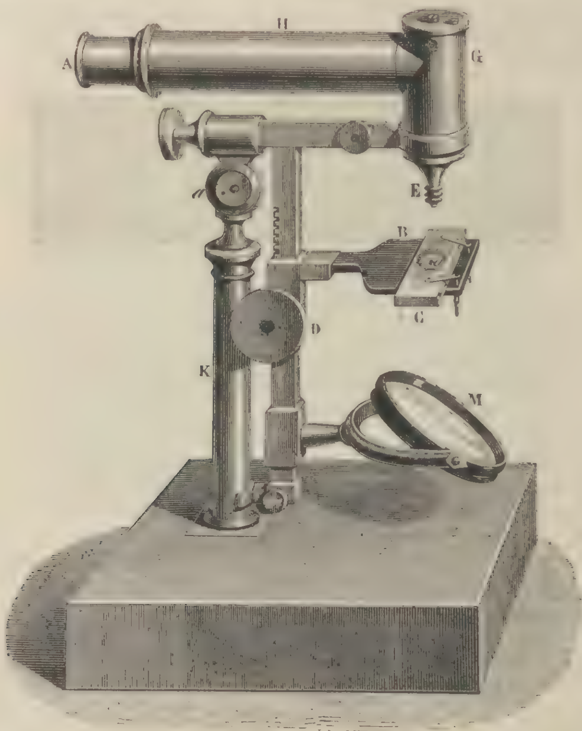


Fig. 419.

Fig. 420 shows the position of the glasses, and the path of the rays in the microscope. The object glass, E, may be formed of one, two, or three lenses ; in this case there are three, whose principal focal distances are 8 to 10 millimeters. The eyepiece is formed of two plano-convex lenses, m and n. The path of the rays is easily followed. The luminous rays, after being refracted from the mirror, M, converge towards the object, o, and are thence directed towards the object glass, E. Having traversed it, they fall on a glass prism, p, on whose hypothenuse they experience total reflection (487). The luminous rays then traverse the tube AB, and, falling on the lens n, form at bc a real and magnified image of the object. The last lens, m, acts as a simple microscope, and instead of this first image forms a second virtual image, $b'c'$, which is still more magnified.

The object of the intermediate lens, n, is to condense the rays which

are too oblique, and which would not fall on the eyeglass, *m*. It enlarges the *field* of the microscope, making the image smaller and more defined. The spherical aberration is corrected by the diaphragms *e* and *e′*; they intercept the rays which pass the lenses too near the edges. In order to

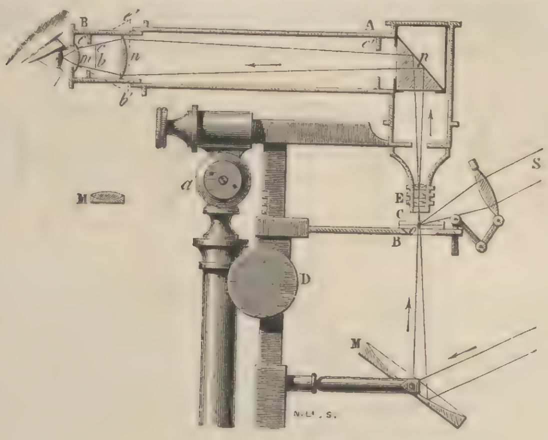


Fig. 420.

extinguish the internal reflection which might injure the precision of the images, the inside of the tube is blackened.

The illumination of the microscope varies according as the object is transparent or opaque. In the former case the object is illuminated as above by means of a reflector placed below the stage. In the second case a condensing lens called the *bull's eye* is used; it is placed on the stage, and concentrates the rays S on the object.

The microscope possesses numerous eyepieces and object glasses, by means of which a great variety of magnifying power is obtained A small magnifying power is also obtained by removing one or two of the lenses of the object glass.

The above contains the essential features of the microscope; it is made in a great variety of forms, which differ mainly in the construction of the stand, the arrangement of the lenses, and in the illumination. For descriptions of these the student is referred to special works on the microscope.

529. **Achromatism of the microscope. Campani's eyepiece.**— When a compound microscope consists of two single lenses, as in fig. 421, not only is the spherical aberration uncorrected, but also the chromatic aberration, the latter defect causing the images to be surrounded by fringes of the prismatic colours, these fringes being larger as the magnification is greater. It is with a view to correcting these aberrations that the object glass (see fig. 420) is composed of three achromatic lenses, and the eyepiece of two lenses, *n* and *m*, for the first of these, *n*, would be enough to produce colour unless the magnifying power were low.

The effect of this eyepiece in correcting the colour may be explained as follows. It will be borne in mind that with respect to red rays the focal length of a lens is *greater* than the focal length of the same lens with reference to the violet rays.

In fact, if equation (4), we write $R' = \infty$, we obtain $f = \frac{R}{n-1}$, which gives the focal length of a plano-convex lens whose refractive index is n. Now,

Fig. 421.

in flint glass, and for the red ray, $n-1$ equals 0·63, and for the violet ray $n-1$ equals 0·67.

Let *ab* be the object, O the object glass which is corrected for colour. Consequently a pencil of rays falling from *a* on O would converge to a focus, A, without any separation of colours, but falling on the *fieldglass* C, the red rays would converge to *r*, the violet rays to *v*, and intermediate colours, to intermediate points. In like manner the rays from *b*, after passing through the fieldglass, would converge to *r'*, *v'*, and intermediate points. So that on the whole there would be formed a succession of coloured images of *ab*. viz. a red image at *rr'*, a violet image at *vv'*, and between them images of intermediate colours. Let *d* be the point of the object which is situated on the axis. The rays from *d* will converge to R, V, and intermediate points. Now suppose the *eyeglass* O' to be placed in such a manner that R is the principal focus of O' for the red rays, then will V be its principal focus for the violet rays. Consequently the red rays, after emerging from O', will be parallel to the axis, and so will the violet rays emerging from V, and so of any other colour. Consequently, the colours of *d*, which are separated by C, are again combined by O'. The same is very nearly true of *r* and *v*, and of *r'* and *v'*. Hence combination of the lenses C and O' corrects the chromatic aberration that would be produced by the use of a single eyeglass. Moreover, by drawing the rays towards the axis, it diminishes the spherical aberration, and, as we shall see in the next article, enlarges the field of view.

In all eyepieces consisting of two lenses the lens to which the eye is applied is called the *eye lens*, the one towards the object glass is called the *field lens*. The eyepiece above described was invented by Huyghens, who was not, however, aware of its property of achromatism. He designed it for use with the telescope. It was applied to the microscope by Campani. The relation between the focal lengths of the lenses is as follows. The focal length of the fieldglass is three times that of the eye lens, and the distance between their centres is half the sum of the focal length. It easily follows from this that the image of the point *d* would.

but for the interposition of the field lens, be formed at D, which is so situated that CD is three times DO′, then the mean of the coloured images will be formed midway between C and O′.

530. **Field of view.**—By the field of view of an optical instrument is meant all those points which are visible through the eyepiece. The advantage obtained by the use of an eyepiece in enlarging the field of

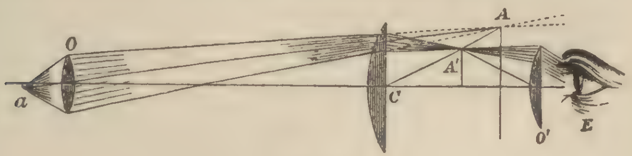


Fig. 422.

view will be readily understood by an inspection of the accompanying figure. As before, O is the object glass, C the field lens, O′ the eye lens, and E the eye placed on the axis of the instrument. Let *a* be a point of the object ; if we suppose the field lens removed, the pencil of rays from *a* would be brought to a focus at A, and none of them would fall on the eye-lens O′, nor pass into the eye E. Consequently *a* is beyond the field of view. But when the field glass C is interposed, the pencil of rays is brought to a focus at A′, and emerges from O′ into the eye. Consequently *a* is now within the field of view. It is in this manner that the substitution of an eyepiece for a single eye lens enlarges the field of view.

531. **Magnifying power. Micrometer.**—The magnifying power of any optical instrument is the ratio of the magnitude of the image to the magnitude of the object. The magnifying power in a compound microscope is the product of the respective magnifying powers of the object glass and of the eyepiece ; that is, if the first of these magnifies 20 times, and the other 10, the total magnifying power is 200. The magnifying power depends on the greater or less convexity of the object glass and of the eyepiece, as well as on the distance between these two glasses, together with the distance of the object from the object glass. A magnifying power of 1500 and even upwards has been obtained ; but the image then loses in sharpness what it gains in extent. To obtain precise and well illuminated images, the magnifying power ought not to exceed 500 to 600 diameters, which gives a superficial enlargement 250,000 to 360,000 times that of the object.

The magnifying power is determined experimentally by means of the *micrometer* ; this is a small glass plate, on which, by means of a diamond, a series of lines is drawn at a distance from each other of $\frac{1}{10}$ or $\frac{1}{100}$ of a millimeter. The micrometer is placed in front of the object glass, and then instead of viewing directly the rays emerging from the eyepiece, O, they are received on a piece of glass, A (fig. 423), inclined at an angle of 45°, and the eye is placed above so as to see the image of the micrometer lines which is formed by reflection on a screen, E, on which is a scale divided into millimeters. By counting the number of divisions of this

scale corresponding to a certain number of lines of the image, the magnifying power may be deduced. Thus, if the image occupies a space of 45 millimeters on the scale, and contains 15 lines of the micrometer, the distance between each of which shall be assumed at $\frac{1}{100}$ millimeter, the absolute magnitude of the object will be $\frac{15}{100}$ millimeter; and as the image occupies a space of 45 millimeters, the magnification will be the quotient of 45 by $\frac{15}{100}$ or 300. The eye in this experiment ought to be at such a distance from the screen, E, that the screen is distinctly visible: this distance varies with different observers, but is usually 10 to 12 inches. The magnifying power of the microscope can also be determined by means of the *camera lucida*.

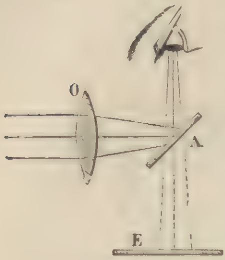


Fig. 423.

When once the magnifying power is known, the absolute magnitude of objects placed before the microscope is easily deduced. For, as the magnifying power is nothing more than the quotient of the size of the image by the size of the object, it follows that the size of the image divided by the magnifying power gives the size of the object; it is in this manner that the diameter of all microscopic objects is determined.

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532. **Astronomical telescope.**—The *astronomical telescope* is used for observing the heavenly bodies; like the microscope, it consists of a condensing eyepiece and object glass. The object glass, M (fig. 424), forms between the eyepiece, N, and its principal focus an inverted image of the heavenly body, and this eyepiece, which acts as a magnifying glass, then

Fig. 424.

gives a virtual and highly magnified image, *a′b′*, of the image *ab*. The astronomical telescope appears, therefore, analogous to the microscope; but the two instruments differ in this respect: that in the microscope, the object being very near the objective, the image is formed much beyond the principal focus, and is greatly magnified, so that both the object glass and the eyepiece magnify; while in the astronomical telescope, the heavenly body being at a great distance, the incident rays are parallel, and the image formed in the principal focus of the object glass is much

smaller than the object. There is, therefore, no magnification except by the eyepiece, and this ought, therefore, to be of very short focal length.

Fig. 425 shows an astronomical telescope mounted on its stand. Above it there is a small telescope, which is called the *finder*. Telescopes with a large magnifying power are not convenient for finding a star, as they have but a small field of view: the position of the star is, accordingly, first sought by the finder, which has a much larger field of view, that is, takes in a far greater extent of the heavens: it is then viewed by means of the telescope.

The magnification (note, art. 526) equals $\frac{ACB}{a'Ob'}$ (fig. 424); that is, it equals $\frac{bCO}{bOC}$, and therefore is approximately equal to $\frac{CF}{OF}$, F being the focus of the object glass, M, and being supposed very nearly to coincide with the focus of the eyepiece, N; it may, therefore, be concluded that the magnifying power is greater in proportion as the object glass is less convergent, and the eyepiece more so.

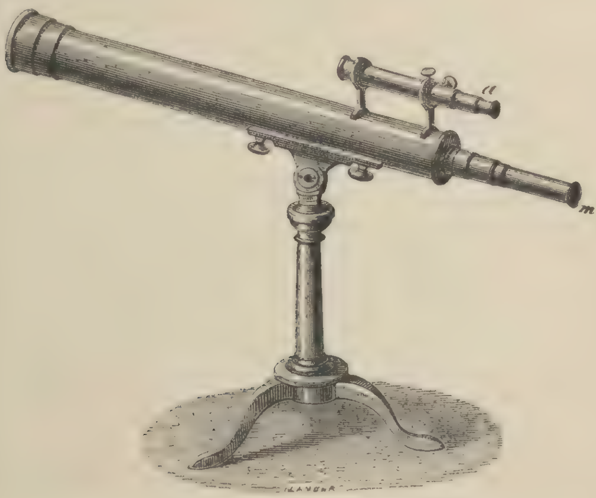


Fig. 425.

When the telescope is used to make an accurate observation of the stars, for example, their zenith distance, or their passage over the meridian, a *cross wire* is added. This consists of two very fine metallic wires or spider threads stretched across a circular aperture in a small metal plate (fig. 426). The wires ought to be placed in the position where the inverted image is produced by the object glass, and the point where the wires cross ought to be on the optical axis of the telescope, which thus becomes the *line of sight* or *collimation*.

Fig. 426.

533. **Terrestrial telescope.**—The *terrestrial telescope* differs from the astronomical telescope in producing images in their right positions. This is effected by means of two condensing glasses, P and Q (fig. 427), placed between the object glass, M, and the eyepiece, R. The object

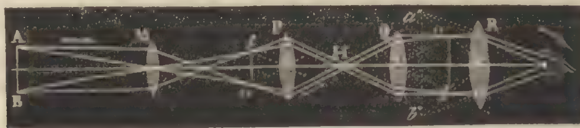


Fig. 427.

being supposed to be at AB, at a greater distance than can be shown in the drawing, an inverted and much smaller image is formed at *ba* on the other side of the object glass. But the second lens, P, is at such a distance that its principal focus coincides with the image *ab*; from which it follows that the luminous rays which pass through *b*, for example, after traversing the lens, P, take a direction parallel to the secondary axis, *b*O (498). Similarly the rays passing by *a* take a direction parallel to the axis, *a*O. After crossing on H, these various rays traverse a third lens, Q, whose principal focus coincides with the point H. The pencil B*b*H converges towards *b'*, on a secondary axis, O'*b*, parallel to its direction; the pencil A*a*H converging in the same manner at *a'*, an erect image of the object, AB, is produced at *a'b'*. This image is viewed, as in the astronomical telescope, through a condensing eyepiece, R, so placed that it acts as a magnifying glass, that is, its distance from the image, *a'b'*, is less than the principal focal distance; hence, there is formed, at *a''b''*, a virtual image of *a'b'*, erect, and much magnified. The lenses P and Q, which only serve to rectify the position of the image, are fixed in a brass tube, at a constant distance, which is equal to the sum of their principal focal distances. The object glass, M, moves in a tube, and can be moved to or from the lens P, so that the image, *ab*, is always formed in the focus of the lens whatever be the distance of the object. The distance of the lens R may also be varied so that the image *a''b''* may be formed at the distance of distinct vision.

This instrument may also be used as an astronomical telescope by using a different eyepiece; this must have a much greater magnifying power than in the former cases.

In the terrestrial telescope the magnifying power is the same as in the astronomical telescope, provided always that the correcting glasses, P and Q, have the same convexity.

534. **Galilean telescope.**—The *Galilean telescope* is the simplest of all telescopes, for it only consists of two lenses, namely, an object glass, M, and a diverging or double concave eyepiece, R (fig. 428), and it gives at once an erect image. *Opera glasses* are constructed on this principle.

If the object be represented by the right line, AB, a real but inverted and smaller image would be formed at *ba*; but in traversing the eyepiece, R, the rays emitted from the points A and B are refracted, and diverge

from the secondary axes, bO' and aO', which correspond to the points b and a of the image. Hence, these rays produced backward meet their

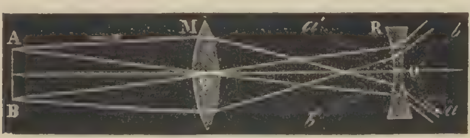


Fig. 428.

axes in a' and b'; the eye which receives them sees accordingly an erect and magnified image in $a'b'$, which appears nearer because it is seen under an angle, $a'O'b'$, greater than the angle, AOB, under which the object is seen.

The magnifying power is equal to the ratio of the angle $a'O'b'$ to the angle AOB, and is usually from 2 to 4.

The distance of the eyepiece R from the image ab is pretty nearly equal to the principal focal distance of this eyepiece; it follows, therefore, that the distance between the two lenses is the difference between their respective focal distances: hence, Galileo's telescope is very short and portable. It has the advantage of showing objects in their right position; and, further, as it has only two lenses, it absorbs very little light: in consequence, however, of the divergence of the emergent rays, it has only a small field of view, and in using it the eye must be placed very near the eyepiece. The eyepiece can be moved to or from the object glass, so that the image $a'b'$ is always formed at the distance of distinct vision.

The opera glass is usually double, so as to produce an image in each eye, by which greater brightness is attained.

The time at which telescopes were invented is not known. Some attribute their invention to Roger Bacon in the 13th century; others to J. B. Porta at the end of the 16th; others again to a Dutchman, Jacques Metius, who, in 1609, accidentally found that by combining two glasses, one concave and the other convex, distant objects appeared nearer and much larger.

Galileo's was the first telescope directed towards the heavens. By its means Galileo discovered the mountains of the moon, Jupiter's satellites, and the spots on the sun.

535. **Reflecting telescopes.**—The telescopes previously described are *refracting* or *dioptric* telescopes. It is, however, only in recent times that it has been possible to construct achromatic lenses of large size; before this, a concave metallic mirror was used instead of the object glass. Telescopes of this kind are called *reflecting* or *catoptric telescopes*. The principal forms are those devised by Gregory, Newton, Herschel, and Cassegrain.

536. **The Gregorian telescope.**—Figure 429 is a representation of Gregory's telescope; it is mounted on a stand, about which it is moveable, and can be inclined at any angle. This mode of mounting is

optional; it may be equatorially mounted. Fig. 430 gives a longitudinal section. It consists of a long brass tube closed at one end by a concave metallic mirror, M, which is perforated in the centre by a round aperture

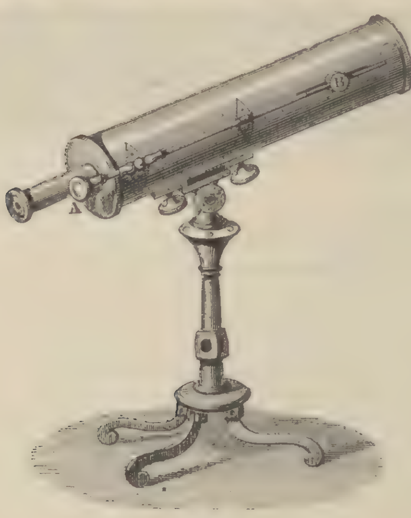


Fig. 429

through which rays reach the eye. There is a second concave metal mirror, N, near the end of the tube; it is somewhat larger than the central aperture in the large mirror, and its radius of curvature is much

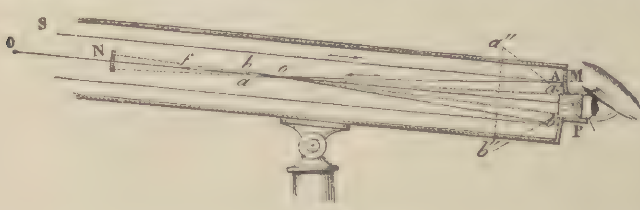


Fig. 430.

smaller than that of the large mirror. The axes of both mirrors coincide with the axis of the tube. As the centre of curvature of the large mirror is at O, and its focus at *ab*, rays, such as SA, emitted from a heavenly body, are reflected from the mirror M, and form at *ab* an inverted and very small image of the heavenly body. The distance of the mirrors and their curvatures is so arranged that the position of this image is between the centre, *o*, and the focus, *f*, of the small mirror; hence the rays, after being reflected a second time from the mirror N, form at *a'b'* a magnified and inverted image of *ab*, and therefore in the true position of the heavenly

body. This image is viewed through an eyepiece, P, which may either be single or compound, its object being to magnify it again so that it is seen at $a''b''$.

As the objects viewed are not always at the same distance, the focus of the large mirror, and therefore that of the small one, vary in position. And as the distance of distinct vision is not the same with all eyes, the image $a''b''$ ought to be formed at different distances. The required adjustments may be obtained by bringing the small mirror nearer or farther from the larger one ; this is effected by means of a milled head, A (fig. 429), which turns a rod, and this by a screw moves a piece to which the mirror is fixed.

537. **The Newtonian telescope.**—This instrument does not differ much from that of Gregory ; the large mirror is not perforated, and there

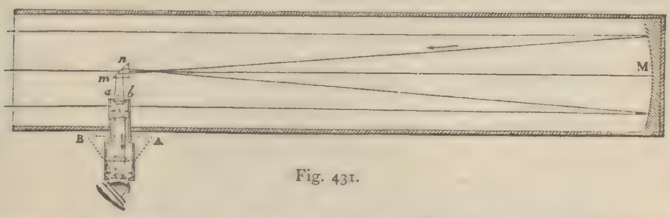


Fig. 431.

is a small plane mirror inclined at an angle of 45° towards an eyepiece placed in the side of the telescope. The difficulty of constructing metallic mirrors has caused telescopes of Gregorian and Newtonian construction to fall into disuse. Of late, however, the process of silvering glass mirrors has been carried to a high state of perfection, and M. Foucault has applied these mirrors to Newtonian telescopes with great success. His first mirror was only four inches in diameter, but he has successively constructed mirrors of 8, 12, and 13 inches, and at the time of his death had completed one of 32 inches diameter.

Fig. 432 represents a Newtonian telescope mounted on an equatorial stand, and fig. 431 gives a horizontal section of it. This section shows how the luminous rays reflected from the parabolic mirror, M, meet a small rectangular prism, *mn*, which replaces the inclined plane mirror used in the old form of Newtonian telescope. After undergoing a total reflection from *mn*, the rays form at *ab* a very small image of the heavenly body. This image is viewed through an eyepiece with four lenses placed on the side of the telescope, and magnifying from 50 to 800 times, according to the size of the silvered mirror.

In reflectors the mirror acts as object glass, but there is, of course, no chromatic aberration.

The spherical aberration is corrected by the form given to the reflector, which is paraboloid, but slightly modified by trial to suit the eyepiece fitted to the telescope.

The mirror once polished is immersed in a silvering liquid, which consists essentially of ammoniacal solution of nitrate of silver, to which some

reducing agent is added. When a polished glass surface is immersed in this solution, silver is deposited on the surface in the form of a brilliant

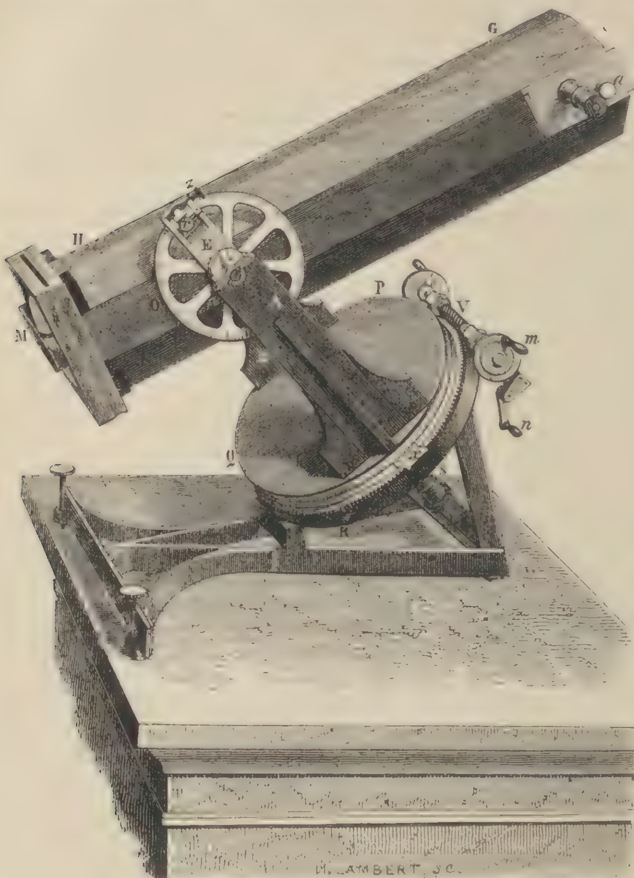


Fig. 432.

metallic layer, which adheres so firmly that it can be polished with rouge in the usual manner.

These new telescopes with glass mirrors have the advantage over the old ones that they give purer images, they weigh less, and are much shorter, their focal distance being only about six times the diameter of the mirror.

These details known, the whole apparatus remains to be described. The body of the telescope (fig. 432) consists of an octagonal wooden tube. The

end, G, is open ; the mirror is at the other end. At a certain distance from this end two axles are fixed, which rest on bearings supported by two wooden uprights, A and B. These are themselves fixed to a table, PQ, which turns on a fixed plate, RS, placed exactly parallel to the equator. On the circumference of the turning table there is a brass circle, divided into 360 degrees, and beneath it, but also fixed to the turning table, there is a circular toothed wheel, in which an endless screw, V, works. By moving this in either direction by means of the handle *m*, the table PQ, and with it the telescope, can be turned. A vernier, *x*, fixed to the plate RS, gives the fractions of a degree. On the axis of the motion of the telescope there is a graduated circle, O, which serves to measure the *declination* of the star, that is, its angular distance from the equator ; while the degrees traced round the table, RS, serve to measure the *right ascension*, that is, the angle which the declination circle of the star makes with the declination circle passing through the first point of Aries.

In order to fix the telescope in declination, there is a brass plate, E, fixed to the upright ; it is provided with a clamp, in which the limb O works, and which can be screwed tight by means of a screw with milled head, *r*. On the side of the apparatus there is the eyepiece, *o*, which is mounted on a sliding copper plate, on which there is also the small prism *mn*, represented in the section fig. 431. To bring the image to the right place, this plate may be moved by means of a rack and a milled head, *a*. The handle, *n*, serves to *clamp* or *unclamp* the screw, V. The drawing was one taken from a telescope, the mirror of which is only 6½ inches in diameter, and which gives a magnifying power of 150 to 200.

538. **The Herschelian telescope.**—Sir W. Herschel's telescope, which, until recently, was the most celebrated instrument of modern times, was constructed on a method differing from those described. The mirror was so inclined that the image of the star was formed at *ab* on the side of the telescope near the eyepiece, *o*, hence it is termed the *front view* telescope.

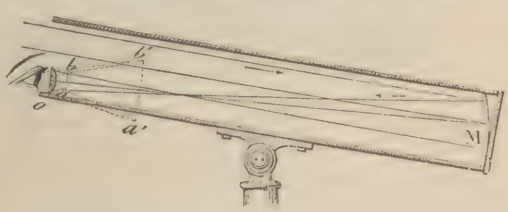


Fig. 433.

As the rays in this telescope only undergo a single reflection, the loss of light is less than in either of the preceding cases, and the image is therefore brighter. The magnifying power is the quotient of the principal focal distance of the mirror by the focal distance of the eyepiece.

Herschel's great telescope was constructed in 1789 ; it was 40 feet in length, the great mirror was 50 inches in diameter. The quantity of light obtained by this instrument was so great as to enable its inventor

to use magnifying powers far higher than anything which had hitherto been attempted.

Herschel's telescope has been exceeded by one constructed by the late Earl of Rosse. This magnificent instrument has a focal length of 53 feet, the diameter of the speculum being 6 feet. It is at present used as a Newtonian telescope, but it can also be arranged as a front view telescope.

INSTRUMENTS FOR FORMING PICTURES OF OBJECTS.

539. **Camera obscura.**—The *camera obscura* (dark chamber) is, as its name implies, a closed space impervious to light. There is, however, a small aperture by which luminous rays enter, as shown in fig. 434. The ray, proceeding from external objects, and entering by this aperture, forms on the opposite side an image of the object in its natural colours, but of reduced dimensions, and in an inverted position.

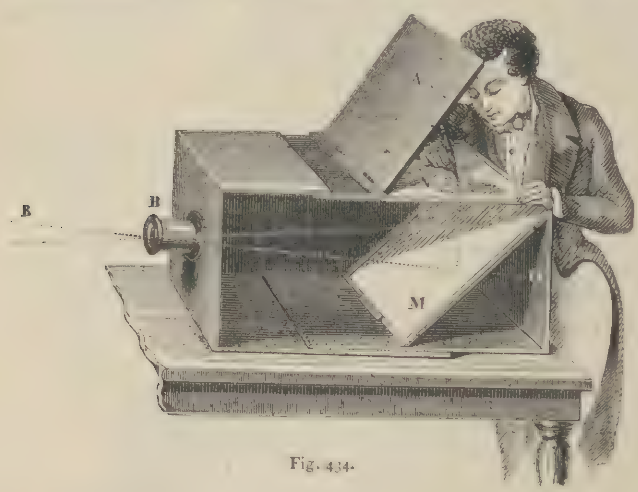


Fig. 434.

Porta, a Neapolitan physician, the inventor of this instrument, found that by fixing a double convex lens in the aperture, and placing a white screen in the focus, the image was much brighter, and more definite.

Fig. 434 represents a camera obscura, such as is used for drawing. It consists of a rectangular wooden box, formed of two parts which slide in and out. The luminous rays, R, pass into the box by a lens, B, and form an image on the opposite side, O, which is at the focal distance of the lens. But the rays are reflected from a glass mirror, M, inclined at an angle of 45°, and form an image on a ground glass plate, N. When a piece of tracing paper is placed on this screen, a drawing of the image is easily made. A wooden door, A, cuts off extraneous light.

The box is formed of two parts, sliding one within the other, like the joints of a telescope, so that, by elongating it more or less, the reflected image may be made to fall exactly on the screen, N, at whatever distance the object may be situated.

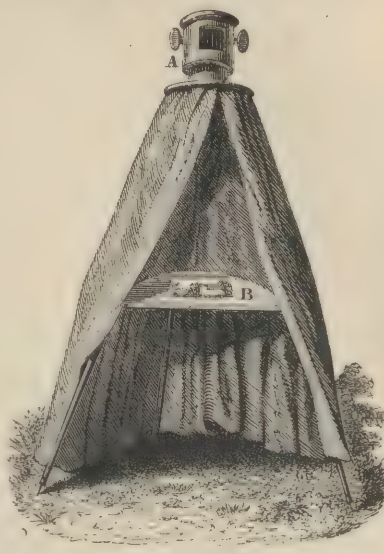


Fig. 435.

Fig. 435 shows another kind of camera obscura, which is occasionally erected in summer houses. In a brass case A there is a triangular prism, P (fig. 436), which acts both as condensing lens and as mirror. One of its faces is plane, but the others have such curvatures that the combined refractions on entering and emerging from the prism produce the effect of a meniscus lens. Hence rays from an object, AB, after passing into the prism, and undergoing total reflection from the face *cd*, form at *ab* a real image of AB.

In fig. 435, the small table B corresponds to the focus of the prism in the case A, and an image forms on a piece of paper placed on the table. The whole is surrounded by a black curtain, so that the designer can place himself in complete darkness.

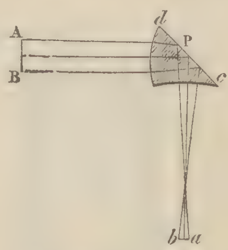


Fig. 436.

540. **Camera lucida.**—The *camera lucida* is a small instrument depending on internal reflection, and serves for taking an outline of any object. It was invented by Dr. Wollaston, in 1804. It consists of a small four-sided glass prism, of which fig. 437 gives a section perpendicular to the edges. A is a right angle, and C an angle of 135°; the other angles, B and D, are $67\frac{1}{2}°$. The prism rests on a stand, on which it can be raised or lowered, and turned more or less about an axis parallel to the prismatic edges. When the face, AB, is turned towards the object, the rays from the object fall nearly perpendicular on this face, pass into the prism without any appreciable refraction, and are totally reflected from BC; for as the line *ab* is perpendicular to BC, and *n*L to AB, the angle *an*L will equal the angle B, that is, it will contain $67\frac{1}{2}°$, and this being greater than the critical angle of glass (487), the ray L*n* will undergo total reflection. The rays are again totally reflected from *o*, and emerge near the summit, D, in a

direction almost perpendicular to the face DA, so that the eye which receives the rays sees at L′ an image of the object L. If the outlines of the

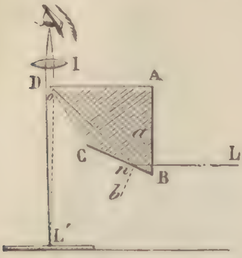


Fig. 437.

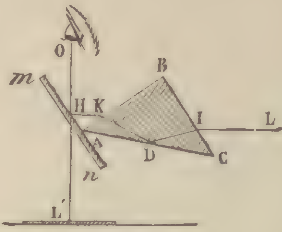
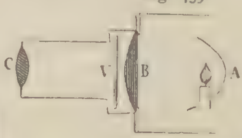


Fig. 438.

image are traced with a pencil, a very correct design is obtained ; but unfortunately there is a great difficulty in seeing both the image and the point of the pencil, for the rays from the object give an image which is farther from the eye than the pencil. This is corrected by placing between the eye and prism a lens, I, which gives to the rays from the pencil and those from the object the same divergence. In this case, however, it is necessary to place the eye very near the edge of the prism, so that the aperture of the pupil is divided into two parts, one of which sees the image, and the other the pencil.

Amici's camera lucida, represented in fig. 438, is preferable to that of Wollaston, inasmuch as it allows the eye to change its condition to a con-

Fig. 439.



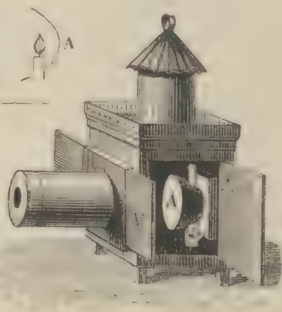


Fig. 440.

siderable extent, without ceasing to see the image and the pencil at the same time. It consists of a rectangular glass prism, ABC, having one of its perpendicular faces turned towards the object to be depicted, while the other is at right angles to an inclined plate of glass, *mn*. The rays, LI, proceeding from the object, and entering the prism, are totally reflected from its base at D, and emerge in the direction KH. They are

then partially reflected from the glass plate *mn* at H, and form a vertical image of the object, L, which is seen by the eye in the direction OL′. The eye, at the same time, sees through the glass the point of a pencil applied to the paper, and thus the outline of the picture may be traced with great exactness.

541. **Magic lantern.**—This is an apparatus by which a magnified image of small objects may be projected on a white screen in a dark room. It consists of a tin plate box, in which there is a lamp placed in the focus of a concave mirror, A (fig. 439). The reflected rays fall upon a condensing lens, B (fig. 439), which concentrates them on the figure painted on a glass plate, V. There is a double convex lens, C, at a distance from V of rather more than its focal distance, and, consequently, a real and very much magnified image of the figure on the glass is produced on the screen (503).

Dissolving views are obtained by arranging two magic lanterns, which are quite alike, with different pictures, in such a manner that both pictures are produced on exactly the same part of a screen. The object glasses of both lanterns are closed by screens, which are so arranged that according as one is raised the other is lowered, and *vice versâ*. In this way one picture is gradually seen to change into the other.

The magnifying power of the magic lantern is obtained by dividing

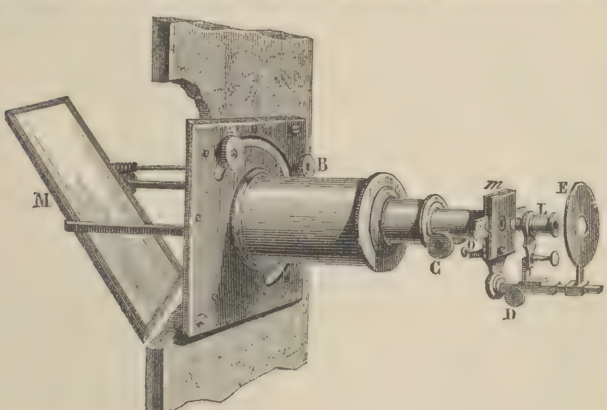


Fig. 441.

the distance of the lens C from the image by its distance from the object. If the image is 100 or 1000 times farther from the lens than the object, the image will be 100 or 1000 times as large. Hence a lens with a very short focus can produce a very large image, provided the screen is sufficiently large.

542. **Solar microscope.**—The solar microscope is in reality a magic lantern illuminated by the solar rays; it serves to produce highly magnified images of very small objects. It is worked in a dark room; fig. 441

represents it fitted in the shutter of a room, and fig. 442 gives the internal details.

The solar rays fall on a plane mirror, M, placed outside the room, and are reflected towards a condensing lens, *l*, and from thence to a second lens, *o* (fig. 442), by which they are concentrated at its focus. The object

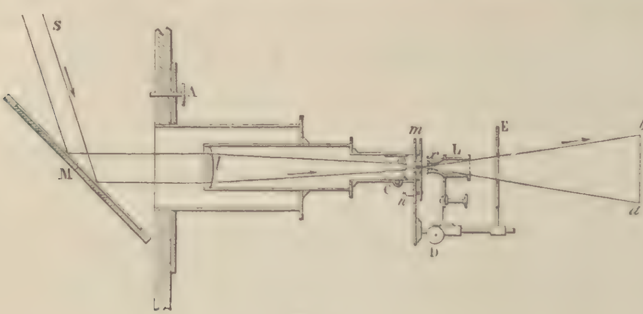


Fig 442.

to be magnified is at this point; it is placed between two glass plates, which, by means of a spring, *n*, are kept in a firm position between two metal plates, *m*. The object thus strongly illuminated is very near the focus of a system of three condensing lenses, *x*, which forms upon a screen at a suitable distance an inverted and greatly magnified image, *ab*. The distance of the lenses, *o* and *x*, from the object is regulated by means of screws, C and D.

As the direction of the solar light is continually varying, the position of the mirror outside the shutter must also be changed, so that the reflection is always in the direction of the axis of the microscope. The most exact apparatus for this purpose is the heliostat (481); but as this instrument is very expensive, the object is usually attained by inclining the mirror to a greater or less extent by means of an endless screw, B, and at the same time turning the mirror itself round the lens *l*, by a knob, A, which moves in a fixed slide.

The solar microscope labours under the objection of concentrating great heat on the object, which soon alters it. This is partially obviated by interposing a layer of a saturated solution of alum, which, being a powerfully athermanous substance, cuts off a considerable portion of the heat.

The magnifying power of the solar microscope may be deduced experimentally by substituting for the object a glass plate marked with lines at a distance of $\frac{1}{10}$ or $\frac{1}{100}$ of a millimeter. Knowing the distance of these lines on the image, the magnifying power may be calculated. The same method is used with the photoelectric light. According to the magnifying power which it is desired to obtain, the objective *x* is formed of one two, or three lenses, which are all achromatic.

The solar microscope furnishes the means of exhibiting to a large

audience many curious phenomena, such, for instance, as the circulation of blood in the smaller animals, the crystallisation of salts, the occurrence of animalculæ in water, vinegar, etc. etc.

543. **Photoelectric microscope.**—This is nothing more than the solar microscope, but is illuminated by the electric light instead of by the sun's rays. The electric light, by its intensity, its steadiness, and the readiness with which it can be procured at any time of the day, is far preferable to the solar light. The photoelectric microscope alone will be described here: the electric light will be considered under the head of Galvanism.

Fig. 443 represents the arrangement devised by M. Duboscq. A solar

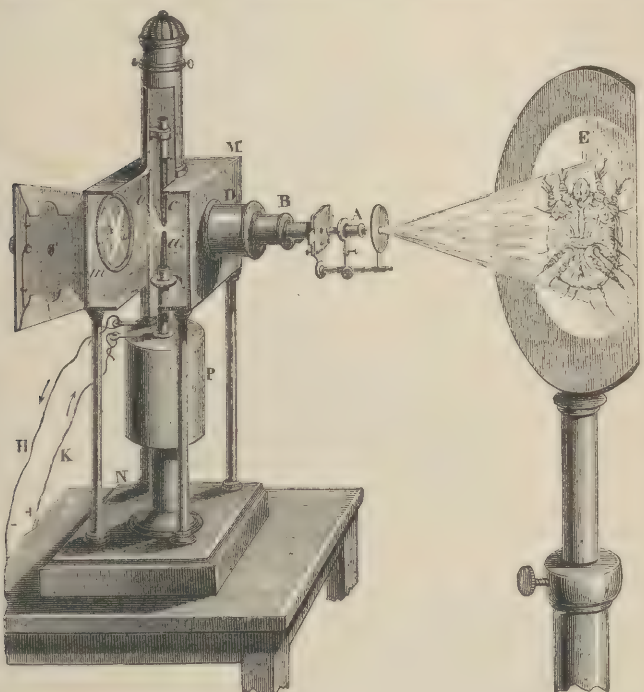


Fig. 443.

microscope, ABD, identical with that already described, is fixed on the outside of a brass box. In the interior are two charcoal points which do not quite touch, the space between them being exactly on the axis of the lenses. The electricity of one end of a powerful battery reaches the charcoal *a* by means of a copper wire, K; while the electricity from the opposite end of the battery reaches *c* by a second copper wire H.

During the passage of the electricity, a luminous arc is formed between the two ends of the carbons, which gives a most brilliant light, and powerfully illuminates the microscope. This is effected by placing at D in the inside of the tube a condensing lens, whose principal focus corresponds to the space between the two charcoals. In this manner the luminous rays, which enter the tubes D and B, are parallel to their axis, and the same effects are produced as with the ordinary solar microscope; a magnified image of the object placed between two plates of glass is produced on the screen.

In continuing the experiment, the two carbons become consumed, and to an unequal extent, *a* more quickly than *c*. Hence, their distance increasing, the light becomes weaker and is ultimately extinguished. In speaking afterwards of this electric light, the working of the apparatus P, which keeps these charcoals at a constant distance, and thus ensures a constant light, will be explained.

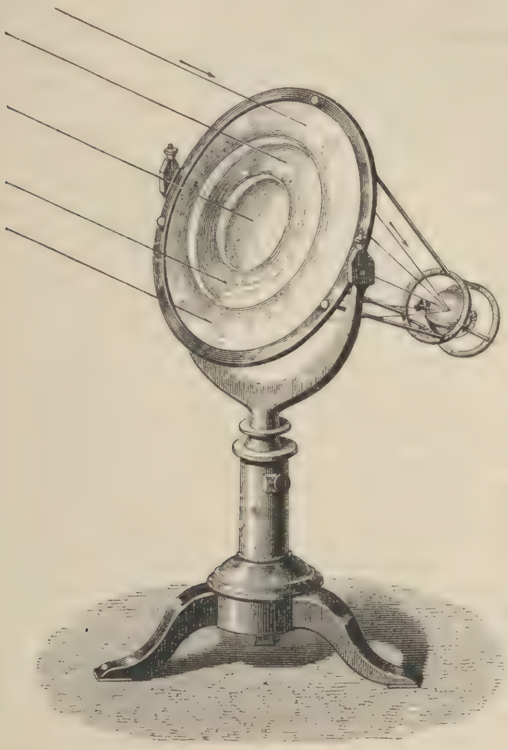
The part of the apparatus, MN, may be considered as a universal *photogenic apparatus*. The microscope can be replaced by the head pieces of the phantasmagoria, the polyorama, the megascope, by polarising apparatus, etc., and in this manner is admirably adapted for exhibiting optical phenomena to a large auditory. Instead of the electric light, we may use with this apparatus the *oxy-hydrogen* or *Drummond's* light, which is obtained by heating a cylinder of lime in the flame produced by the combustion of a mixture of hydrogen and oxygen gases.

544. **Lighthouse lenses.**—Lenses of large dimensions are very difficult of construction; they further produce a considerable spherical aberration, and their thickness causes the loss of much light. In order to avoid these inconveniences, *échelon* lenses have been constructed. They consist of a plano-convex lens, C (figs. 444 and 445), surrounded by a series of annular and concentric segments, A, B, each of which has a plane face on the same side as the plane face of the central lens, while the faces on the other side have such a curvature that the foci of the different segments coincide in the same point. These rings form, together with the central lens, a single lens, a section of which is represented in figure 394. The drawing was made from a lens of about 2 feet in diameter, the segments of which are formed of a single piece of glass; but with larger lenses, each segment is likewise formed of several pieces.

Behind the lens there is a support fixed by three rods, on which a body can be placed and submitted to the sun's rays. As the centre of the support coincides with the focus of the lens, the substances placed there are melted and volatilised by the high temperature produced. Gold, platinum, and quartz are rapidly melted. This experiment proves that heat is refracted in the same way as light: for the position of the calorific focus is identical with that of the luminous focus.

Formerly parabolic mirrors were used in sending the light of beacons and lighthouses to great distances, but they have been supplanted by the use of lenses of the above construction. In most cases, oil is used in a lamp of peculiar construction, which gives as much light as 20 moderators. The light is placed in the principal focus of the lens on the side of the

plane face. The emergent rays consequently form a parallel beam (fig. 386), which loses intensity only by passing through the atmo-



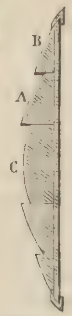


Fig. 445.

Fig. 444.

sphere, and can be seen at a distance of above 40 miles. In order that all points of the horizon may be successively illuminated, the lens is continually moved round the lamp by a clock-work motion, the rate of which varies with different lighthouses. Hence, in different parts, the light alternately appears and disappears after equal intervals of time. These alternations serve to distinguish lighthouses from an accidental fire or a star. By means too of the number of times the light disappears in a given time, and by the colour of the light, sailors are enabled to distinguish the lighthouses from one another, and hence to know their position.

Of late years the use of the electric light has been substituted for that of oil lamps ; a description of the apparatus will be given in a subsequent chapter.

PHOTOGRAPHY.

545. **Daguerreotype.**—*Photography* is the art of fixing the images of the camera obscura on substances *sensitive* to light. The various photographic processes may be classed under three heads: photography on metal, photography on paper, and photography on glass.

Wedgwood was the first to suggest the use of chloride of silver in fixing the image, and Davy, by means of the solar microscope, obtained images of small objects on paper impregnated with chloride of silver; but no method was known of preserving the images thus obtained, by preventing the further action of light. Niepce, in 1814, obtained permanent images of the camera by coating glass plates with a layer of a varnish composed of bitumen dissolved in oil of lavender. This process was tedious and inefficient, and it was not until 1839 that the problem was solved. In that year, Daguerre described a method of fixing the images of the camera, which, with the subsequent improvements of Talbot and Archer, has rendered the art of photography one of the most marvellous discoveries ever made, either as to the beauty and perfection of the results, or as to the celerity with which they are produced.

In Daguerre's process, the *Daguerreotype*, the picture is produced on a plate of copper coated with silver. This is first very carefully polished, an operation on which much of the success of the subsequent operations depends. It is then rendered *sensitive* by exposing it to the action of iodine vapour, which forms a thin layer of iodide of silver on the surface. The plate is now fit to be exposed in the camera; it is sensitive enough for views which require an exposure of ten minutes in the camera, but when greater rapidity is required, as for portraits, etc., it is further exposed to the action of an *accelerator*, such as bromine or hypobromite of calcium. All these operations must be performed in a room lighted by a candle, or by the daylight admitted through yellow glass, which cuts off all chemical rays. The plate is preserved from the action of light by placing it in a small wooden case provided with a slide on the sensitive side.

The third operation consists in exposing the sensitive plate to the action of light, placing it in that position in the camera where the image is produced with greatest delicacy. For photographic purposes a camera obscura of peculiar construction is used. The brass tube A (fig. 446) contains an achromatic condensing lens, which can be moved by means of a rackwork motion, to which is fitted a milled head, D. At the opposite end of the box is a ground-glass plate, E, which slides in a groove, in which the case containing the plate also fits. The camera being placed in a proper position before the object, the sliding part of the box is adjusted until the image is produced on the glass with the utmost sharpness; this is, when the glass slide is exactly in the focus. The final adjustment is made by means of the milled head, D.

The glass slide is then replaced by the case containing the sensitive

plate; the slide which protects it is raised; and the plate exposed for a time, the duration of which varies in different cases, and can only be

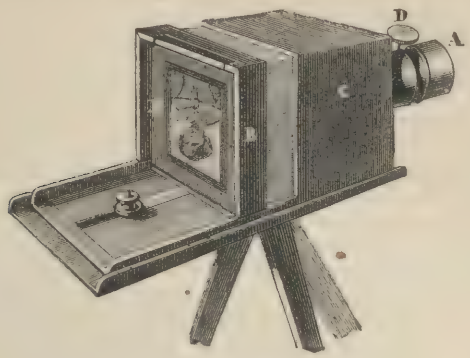


Fig. 446.

hit exactly by great practice. The plate is then removed to a dark room. No change is perceptible to the eye, but those parts on which the light has acted have acquired the property of condensing mercury: the plate is next placed in a box and exposed to the action of mercurial vapour at 60 or 70 degrees.

The mercury is deposited on the parts affected in the form of globules imperceptible to the naked eye. The shadows, or those parts on which the light has not acted, remain covered with the layer of iodide of silver. This is removed by treatment with hyposulphite of sodium, which dissolves iodide of silver without affecting the rest of the plate. The plate is next immersed in a solution of chloride of gold in hyposulphite of sodium, which dissolves the silver, while some gold combines with the mercury and silver of the parts attacked, and greatly increases the intensity of the lustre.

Hence the light parts of the image are those on which the mercury has been deposited, and the shaded those on which the metal has retained its reflecting lustre.

Fig. 447 represents a section of the object glass. At first it consisted of a double convex lens, but now double achromatic lenses are used as object glasses. They act more quickly than objectives with a single lens, and can be more easily focussed by moving the lens B, by means of the rack and pinion D.

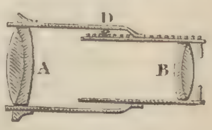


Fig. 447.

546. **Photographs on paper.**—In Daguerre's process, which has just been described, the images are produced directly on metallic plates. With paper and glass, photographs of two kinds may be obtained: those in which an image is obtained with reversed tints, so that the lightest parts have become the darkest on paper, and *vice versâ*; and those in which

the lights and shades are in their natural position. The former are called *negative* and the latter *positive* pictures.

A negative may be taken either on glass or on paper; it serves to produce a positive picture.

Negatives on glass. A glass plate of the proper size is carefully cleaned; collodion impregnated with iodide of potassium is then poured upon it, and the plate moved about till a layer of collodion of uniform thickness is obtained. The plate is then immersed for about a minute in a bath of nitrate of silver containing 30 grains of the salt in an ounce of water. This operation must be performed in a dark room. The plate is then removed, allowed to drain, and when somewhat dry, placed in the closed frame, and afterwards exposed in the camera, for a shorter time than in the case of a Daguerreotype. On removing the plate to a dark room, no change is visible, but on pouring over it a solution called the *developer*, an image gradually appears. The principal substances used for developing are protosulphate of iron and pyrogallic acid. The action of light on iodide of silver appears to produce some molecular change, in virtue of which the developers have the property of reducing to the metallic state those parts of the iodide of silver which have been most acted upon by the light. When the picture is sufficiently brought out, water is poured over the plate, in order to prevent the further action of the developer. The parts on which light has not acted are still covered with iodide of silver, which would be affected if the plate were now exposed to the light. It is, accordingly, washed with solution of hyposulphite of sodium, which dissolves the iodide of silver and leaves the image unaltered. The picture is then coated with a thin layer of spirit-varnish, to protect it from mechanical injury.

When once the negative is obtained, it may be used for printing an indefinite number of positive pictures. For this purpose, paper is impregnated with chloride of silver, by immersing it first in solution of nitrate of silver and then in one of chloride of sodium; chloride of silver is thus formed on the paper by double decomposition. The negative is placed on a sheet of this paper in a copying frame, and exposed to the action of light for a certain time. The chloride of silver becomes acted upon—the light parts of the negative being most affected, and the dark parts least so. A copy is thus obtained, on which the lights of the negative are replaced by shades, and inversely. In order to fix the picture, it is washed in a solution of hyposulphite of sodium, which dissolves the unaltered chloride of silver. The picture is afterwards immersed in a bath of chloride of gold, which gives it tone.

547. **Positives on glass.**—Very beautiful positives are obtained by preparing the plates as in the preceding cases; the exposure in the camera, however, is not nearly so long as for the negatives. The picture is then developed by pouring over it a solution of protosulphate of iron, which produces a negative image; and by afterwards pouring a solution of cyanide of potassium over the plate, this negative is rapidly converted into a positive. It is then washed and dried, and a coating of varnish poured over the picture.

548. **Photographs on albumenised paper and glass.**—In some cases, paper impregnated with a solution of albumen containing iodide of potassium is used instead of collodion, over which it has the advantage that it can be prepared for some time before it is used, and that it produces certain effects in the middle tints. It has the disadvantage of not being nearly so sensitive. It requires, therefore, longer exposure, and is unsuitable for portraits, but can be advantageously used for views.

CHAPTER VI.

THE EYE CONSIDERED AS AN OPTICAL INSTRUMENT.

549. **Structure of the human eye.**—The *eye* is the organ of *vision*, that is to say, of the phenomenon by virtue of which the light emitted or reflected from bodies excites in us the sensation which reveals their presence.

The eye is placed in a bony cavity called the orbit ; it is maintained in its position by the muscles which serve to move it, by the optic nerve, the conjunctiva, and the eyelids. Its size is much the same in all persons : it is the varying aperture of the eyelids that makes the eye appear larger or smaller.

Fig. 448 represents a transverse section of the eye from back to front. The general shape is that of a spheroid, the curvature of which is greater in the anterior than in the posterior part. It is composed of the following parts : the *cornea*, the *sclerotica*, the *iris*, the *pupil*, the *aqueous humour*

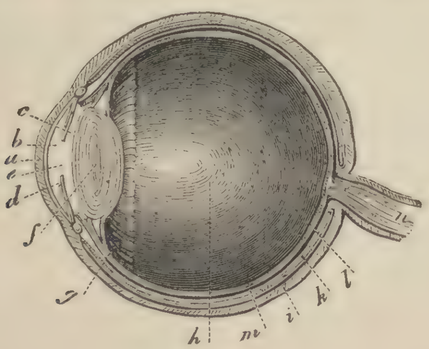


Fig. 448.

the *crystalline*, the *vitreous body*, the *hyaloid membrane*, the *choroid*, the *retina*, and the *optic nerve*.

Cornea. The cornea, *a*, is a transparent membrane situated in front of the ball of the eye. In shape it resembles a small watch glass, and it fits

into the sclerotica, *i*; in fact, these membranes are so connected that some anatomists have considered them as one and the same, and have distinguished them by calling the cornea the *transparent*, and the sclerotica the *opaque* cornea.

Sclerotica. The sclerotica, *i*, or *sclerotic* coat, is a membrane which, together with the cornea, envelopes all parts of the eye. In front there is an almost circular aperture into which the cornea fits; behind it is perforated so as to give passage to the optic nerve.

Iris. The iris, *d*, is an annular, opaque diaphragm, placed between the cornea and the crystalline lens. It constitutes the coloured part of the eye, and is perforated by an aperture called the *pupil*, which in man is circular. In some animals, especially those belonging to the genus *felis*, it is narrow and elongated in a vertical direction: in the ruminants it is elongated in a transverse direction. It is a contractile membrane, and its diameter varies in the same individual between 0·12 and 0·28 of an inch; but these limits may be exceeded. The luminous rays pass into the eye through the pupil. The pupil enlarges in darkness, but contracts under the influence of a bright light. These alternations of contraction and enlargement take place with extreme rapidity; they are very frequent, and play an important part in the act of vision. The movements of the iris are involuntary.

It appears from this description that the iris is a screen with a variable aperture, whose function is to regulate the quantity of light which penetrates into the eye: for the size of the pupil diminishes as the intensity of light increases. The iris serves also to correct the spherical aberration, as it prevents the marginal rays from passing through the edges of the crystalline lens. It thus plays the same part with reference to the eye that a diaphragm does in optical instruments (504).

Aqueous humour. Between the posterior part of the cornea and the front of the crystalline, there is a transparent liquid called the aqueous humour. The space, *e*, occupied by this humour is divided into two parts by the iris; the part *b*, between the cornea and the iris, is called the *anterior chamber*; the part *c*, which is between the iris and the crystalline, is the *posterior chamber*.

Crystalline. The crystalline or *crystalline lens* is a lens-shaped body, *f*, placed behind the iris, but very near it. The crystalline is remarkable for its transparence; it is enclosed in a similar transparent membrane called the *capsule*, which adheres by its edge to an annular wreath called the *ciliary ligament*, *g*.

The convexity of the anterior face of the crystalline is less than that of the posterior. It is made up of a series of *layers* which are almost concentric, and are harder at the centre than at the circumference. The outermost layers are so soft as to be almost liquid. They have been called *Morgagni's humour*. The refracting power of these layers decreases from the centre to the circumference.

Vitreous body. Hyaloid membrane. The vitreous body, or vitreous humour, is a transparent mass resembling the white of an egg, which occupies all the part of the ball of the eye, *h*, behind the crystalline.

The vitreous humour is surrounded by the *hyaloid membrane*, *l*, which lines the posterior face of the crystalline capsule, and also the internal face of another membrane called the retina.

Retina. Optic nerve. The retina, *m*, is a membrane which receives the impression of light, and transmits it to the brain by the intervention of a nerve, *n*, called the optic nerve, which, proceeding from the brain, penetrates into the eye, and extends over the retina in the form of a nervous network.

The only property of the retina and optic nerve is that of receiving and transmitting to the brain the impression of objects. These organs have been cut and pricked without causing any pain to the animals submitted to these experiments.

Choroid. The choroid, *k*, is a membrane between the retina and the sclerotica. It is completely vascular, and is covered on the internal face by a black substance which resembles the colouring matter of a negro's skin, and which absorbs all rays not intended to co-operate in producing vision.

The choroid elongates in front, and forms a series of convoluted folds called *ciliary processes*, which penetrate between the iris and the crystalline capsule to which they adhere, forming round it a disc, resembling a radiated flower. By its vascular tissue, the choroid serves to carry the blood into the interior of the eye, and especially to the ciliary processes.

550. **Refractive indices of the transparent media of the eye.**—The refractive indices from air into the transparent parts of the eye have been determined by Brewster. His results are contained in the following table, compared with water as a standard :

Water	1·3358
Aqueous humour	1·3366
Vitreous humour	1·3394
Exterior coating of the crystalline	1·3767
Centre of the crystalline	1·3990
Mean refraction of the crystalline	1·3839

551. **Curvatures and dimensions of various parts of the human eye.**

Radius of curvature of the sclerotica	0·40 to 0·44 in.
" " cornea	0·28 to 0·32 "
" " anterior face of the crystalline	0·28 to 0·40 "
" " posterior face	0·20 to 0·24 "
Diameter of the iris	0·44 to 0·48 "
" " pupil	0·12 to 0·28 "
" " crystalline	0·40 "
Thickness of the crystalline	0·20 "
Distance from the pupil to the cornea	0·08 "
Length of the axis of the eye	0·88 to 0·96 "

The curvature of the cornea, according to M. Chossat, is that of an

ellipsoid of revolution round its major axis, and the curvature of the crystalline that of an ellipsoid of revolution round its minor axis.

552. **Path of rays in the eye.**—From what has been said as to the structure of the eye, it may be compared to a camera obscura (539), of which the pupil is the aperture, the crystalline is the condensing lens, and the retina is the screen on which the image is formed. Hence, the effect is the same on which the image of an object placed in front of a double convex lens is formed in its conjugate focus. Let AB (fig. 449)

Fig. 449.

be an object placed before the eye, and let us consider the rays emitted from any point of the object A. Of all these rays those which are directed towards the pupil are the only ones which penetrate the eye, and are operative in producing vision. These rays, on passing into the aqueous humour, experience a first refraction which brings them near the secondary axis, A*a*, drawn through the optic centre of the crystalline; they then traverse the crystalline, which again refracts them like a double convex lens, and having experienced a final refraction by the vitreous humour, they meet in a point, *a*, and form the image of the point A. The rays issuing from the point B form in like manner an image of it at the point *b*, so that a very small, real, and inverted image is formed exactly on the retina, provided the eye is in its normal condition.

553. **Inversion of images.**—In order to show that the images formed on the retina are really inverted, the eye of an albino or any animal with pink eyes may be taken; this has the advantage that, as the choroid is destitute of pigment, light can traverse it without loss. This is then deprived at its posterior part of the cellular tissue surrounding it, and fixed in a hole in the shutter of a dark room; by means of a lens it may be seen that inverted images of external objects are depicted on the retina.

The inversion of images in the eye has greatly occupied both physicists and physiologists, and many theories have been proposed to explain how it is that we do not see inverted images of objects. Some have supposed that it is by custom, and by a regular education of the eye, that we see objects in their true position, that is to say, in their position relative to us. The visual impression becomes corrected by the impression of other senses, such as that of touch. Müller, Volkmann, and others contended that, as we see everything inverted, and not simply one object among others, nothing can appear inverted, because terms of comparison are wanting. It must, however, be admitted that none of these theories is quite satisfactory.

554. **Optic axis, optic angle, visual angle.**—The *principal optic axis* of an eye is the axis of its figure; that is to say, the straight line in reference to which it is symmetrical. In a well-shaped eye it is the straight line passing through the centre of the pupil and of the crystalline, such as the line O*o* (fig. 449). The lines A*a*, B*b*, which are almost rectilinear, are secondary axes. The eye sees objects most distinctly in the direction of the principal optic axis.

The *optic angle* is the angle BAC (fig. 450), formed between the

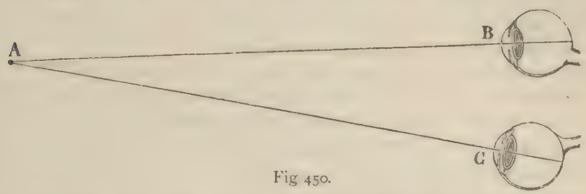


Fig 450.

principal optic axes of the two eyes when they are directed towards the same point. This angle is smaller in proportion as the objects are more distant.

The *visual angle* is the angle AOB (fig. 451), under which an object is seen; that is to say, the angle formed by the secondary axes drawn from

Fig. 451.

the optic centre of the crystalline to the opposite extremities of the object. For the same distance, this angle decreases with the magnitude of the object, and for the same object it decreases as the distance increases, as is the case when the object passes from AB to A′B′. It follows, therefore, that objects appear smaller in proportion as they are more distant; for as the secondary axes, AO, BO, cross in the centre of the crystalline, the size of the image projected on the retina depends on the size of the visual angle, AOB.

555. **Estimation of the distance and size of objects.**—The estimation of distance and of size depends on numerous circumstances; these are—the visual angle, the optic angle, the comparison with objects whose size is familiar to us, the diminution of the precision of the image by the interposition of a more or less vaporous medium.

When the size of an object is known, as the figure of a man, the height of a tree, or of a house, the distance is estimated by the magnitude of the visual angle under which it is seen. If its size is unknown, it is judged relatively to that of objects which surround it.

A colonnade, an avenue of trees, the gas-lights on the side of a road

appear to diminish in size in proportion as their distance increases, because the visual angle decreases; but the habit of seeing the columns, trees, etc., in their proper height, leads our judgment to rectify the impression produced by vision. Similarly, although very distant mountains are seen under a very small angle, and occupy but a small space in the field of view, our familiarity with the effects of aërial perspective enables us to form a correct idea of their real magnitude.

The optic angle is also an essential element in appreciating distance. This angle increasing or diminishing according as objects approach or recede, we move our eyes so as to make their optic axes converge towards the object which we are looking at, and thus obtain an idea of its distance. Nevertheless, it is only by long custom that we can establish a relation between our distance from the objects and the corresponding motion of the eyes. It is a curious fact that persons born blind, and whose sight has been restored by the operation for cataract, imagine at first that all objects are at the same distance.

556. **Distance of distinct vision.**—The *distance of distinct vision* is, as already stated, the distance at which objects must be placed so as to be seen with the greatest distinctness. It varies in different individuals, and in the same individual it is often different in the two eyes. For small objects, such as print, it is from 10 to 12 inches in normal cases.

In order to obtain an approximate measurement of the least distance of distinct vision, two small parallel slits are made in a card at a distance of 0·03 of an inch. These apertures are held close before the eye, and when a fine slit in another card is held very near these apertures, the slit is seen double, because the rays of light which have traversed both apertures do not intersect each other on the retina, but behind it. But, if the latter card is gradually removed, the distance is ultimately reached at which both images coincide and form one distinct image. Stampfer has constructed an *optometer* on this principle.

Persons who see only at a very short distance are called *myoptic*, or *short-sighted*, and those who see only at a long distance are *presbyoptic*, or *long-sighted*.

557. **Adaptation of the eye to all distances.**—The eye has a remarkable property which is not met with to the same extent in any optical instrument. It is, that, although images have a tendency to be formed so much the more in front of the retina as the objects are more distant, they are really formed on the retina; for the eye sees clearly at various distances besides that of distinct vision. But although we can see at very unequal distances, we cannot do so simultaneously, which indicates some modifications in the system of the eye, or, at all events, the necessity of fixing our attention on the object which we wish to see. If, for example, we look at two objects, one of which is at the distance of a yard from the eye, and the other at two yards, when we fix our attention on the first, the second becomes dim, and if on the second, the first in turn becomes indistinct. Hence, it is concluded that when the eye is adapted to see at one distance, it is not in a condition to see at another, but that it can adapt itself either to the one or to the other.

Several hypotheses have been proposed to explain how it is that the eye can see distinctly at various distances. M. Mile thinks that the luminous rays undergo a diffraction or inflexion on the edge of the iris, which produces very different focal distances. Relying on the unequal refrangibility of the crystalline, which decreases from the centre to the circumference, and observing that a series of foci would result, of which the nearest are formed by rays which traverse the crystalline nearest its centre, M. Pouillet assumes that, as the pupil opens to a greater or less extent, distant objects are seen by rays passing near the edge of the crystalline, and less remote objects by rays passing near the centre. Contractions and dilatations of the pupillary aperture are, in fact, connected with the accommodation of the eye to distance; but they are also connected with variations in the intensity of light, and for the same distance the aperture of the pupil may vary greatly.

Rohaut, Olbers, and others have suggested that the diameter of the eye from the back to the front is changed by the muscles which move it, so as to bring the retina nearer to or farther from the cystalline, at the same time that the image itself is nearer or farther ; we know, in fact, that in converging lenses (497) the image is nearer in proportion as the object is more distant.

Hunter and Young attributed to the crystalline a contractile property, in virtue of which it takes a more or less convex form, so as always to cause the rays to converge upon the retina. Kepler, Camper, and others assumed that, by the action of the ciliary processes, the crystalline is moved nearer to or farther from the retina.

It has lastly been supposed that distinctness of vision at various distances may arise from the fact that the differences in the focal distance in the crystalline, in proportion as objects become more distant, are so small that the image retains sufficient distinctness. This is confirmed by the experiments of Magendie and by those by De Haldat. The former observed, with the eye of an albino, that the precision of the images did not vary for objects placed at very unequal distances ; and De Haldat has found that, if a crystalline be placed as an object glass in the shutter of a dark room, equally distinct images of external objects may be obtained on a ground-glass screen, whether the objects be at a distance of 10 or 12 inches, or of 20 to 30 yards. This property of the crystalline in the inert state appears contrary to the laws of refraction ; it is doubtless to be attributed to its structure, which is totally different from that of ordinary lenses. De Haldat has offered no explanation of these phenomena ; the following theory is due to Sturm.

558. **Sturm's theory of vision.**—In order to explain the adaptability of the eye to various distances, Sturm observes that, as it has been shown by Young, Chossat, and others, that the curvatures of the different media of the eye are not spherical, this organ cannot be regarded exactly as a system of homogeneous spherical lenses superposed on the same axis, and that the crystalline especially cannot be compared to an ordinary spherical lens. The eye must be considered as formed of many unequally refracting media, bounded by surfaces which not only are not spherical,

but which do not even form a system symmetrical round a common axis. This being the case, Sturm, premising certain considerations relative to surfaces known in mathematics under the name of *skew surfaces*, investigates the form which a very thin pencil of rays would take, which is successively refracted in several unequally refracting media. Considering the case in which the pencil traverses a diaphragm of very small aperture, whose plane is perpendicular to the axis of the beam, and supposing the beam to emanate from a point situate on the axis, Sturm finds by calculation that the successive intersections of the rays form a caustic surface (480), which cuts the axis of the beam in two points, and that between these two points the beam is more condensed than elsewhere, but beyond it is more and more divergent. Sturm has called these two points, which we designate by the letters F and *f*, the *foci* of the beam, and the distance which separates them is the focal interval.

Applying these theoretical considerations to vision, Sturm advances a theory which may be stated thus : The place in which light can act upon the retina is not a single point, but a *linear focus*, F*f*, in all the extent of which the luminous beam, which penetrates into the pupil, is so condensed as to give rise to the sensation of vision. Consequently, when external objects approach or recede, it is enough for distinct vision that the retina be always comprised between the two foci, F and *f*, or coincide with one of them.

559. **Binocular vision.**—A single eye sees most distinctly any point situated on its optical axis, and less distinctly other points also, towards which it is not directly looking, but which still are within its circle of vision.

It is able to judge of the *direction* of any such point, but unable by itself to estimate its *distance*. Of the distance of an *object* it may indeed learn to judge by such criteria as loss of colour, indistinctness of outline, decrease in magnitude, etc. ; but if the object is near, the single eye is not infallible, even with these aids.

When the two eyes are directed upon a single point, we then gain the power of judging of its distance as compared with that of any other point, and this we seem to gain by the sense of greater or less effort required in causing the optical axes to converge upon the one point or upon the other. Now a solid object may be regarded as composed of points which are at different distances from the eye. Hence, in looking at such an object, the axes of the two eyes are rapidly and insensibly varying their angle of convergence, and we as rapidly are gaining experience of the difference in distance of the various points of which the object is composed, or, in other words, an assurance of its solidity. Such kind of assurance is necessarily unattainable in monocular vision.

560. **The principle of the stereoscope.**—Let any solid object, such as a small box, be supposed to be held at some short distance before the two eyes. On whatever point of it they are fixed, they will see that point the most distinctly, and other points more or less clearly. But it is evident that, as the two eyes see from different points of view, there will be formed in the right eye a picture of the object different from that

formed in the left; and it is by the apparent union of these two dissimilar pictures that we see the object in relief. If, therefore, we delineate the object, first as seen by the right eye, and then as seen by the left, and

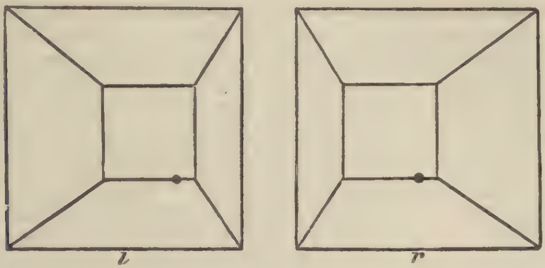


Fig. 452.

afterwards present these dissimilar pictures again to the eyes, taking care to present to each eye that picture which was drawn from its point of view, there would seem to be no reason why we should not see a representation of the object as we saw the object itself, in relief. Experiment confirms the supposition. If the object held before the eyes were a truncated pyramid, *r* and *l*, fig. 452, would represent its principal lines, as seen by the right and left eyes respectively. If a card be held between the figures, and they are steadily looked at, *r* by the right eye, and *l* simultaneously by the left, for a few seconds, there will be seen a single picture having the unmistakeable appearance of relief. Even without a card interposed, the eye, by a little practice, may soon be taught so to combine the two as to form this solid picture. Three pictures will in that case be seen, the central being solid, and the two outside ones plane. Fig. 453 will explain this. Let *r* and *l* be any two corresponding points, say the points marked by a large dot in the figures drawn above; R and L the positions of the right and left eyes; then the right eye sees the point *r* in the direction R*o*, and the left eye the point *l* in the direction L*o*, and accordingly, each by itself judging only by the direction, they together see these two points as one, and imagine it to be situated at *o*. But the right eye, though looking in the direction R*r*, also receives an image of *l* on another part of the retina, and the left eye in the same way an image of *r*, and thus three images are seen. A card, however, placed in the position marked by the dotted line, will of course cut off the two side pictures. To assist the eye in combining such pairs of dissimilar pictures, both mirrors and lenses

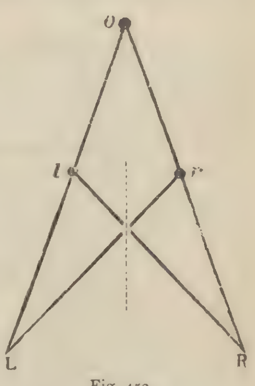


Fig. 453.

have been made use of, and the instruments in which either of these are adapted to this end are called *stereoscopes.*

561. **The reflecting stereoscope.**—In the reflecting steroscope plane mirrors are used to change the apparent position of the pictures, so that they are both seen in the same direction, and their combination by the eye is thus rendered easy and almost inevitable. If *ab ab* (fig. 454) are two plane mirrors inclined to one another at an angle of 90°, the two arrows, x, y, would both be seen by the eyes situated at R and L in the position marked by the dotted arrow. If, instead of the arrows, we now substitute such a pair of dissimilar pictures as we have spoken of above, of the same solid object, it is evident that, if the margins of the pictures coincide, other corresponding points of the pictures will not. The eyes, however, almost without effort, soon bring such points into coincidence, and in so doing make them appear to recede or advance, as they are farther apart or nearer together than any two corresponding points (the right-hand corner, for instance) of the margins, when the pictures are placed side by side, as in the diagram, fig. 454. It will be

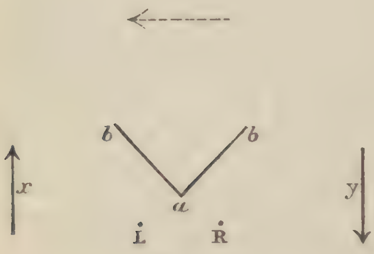


Fig. 454.

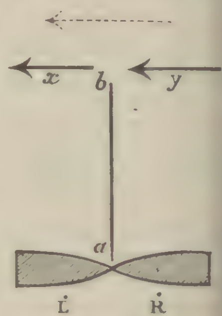


Fig. 455.

plain, also, on considering the position for the arrows in fig. 454, that to adapt such pictures as those in fig. 452 to use in a reflecting stereoscope, one of them must be reversed, or drawn as it would be seen through the paper if held up to the light.

562. **The refracting stereoscope.**—Since the rays passing through a convex lens are bent always towards the thicker part of the lens, any segment of such a lens may be readily adapted to change the apparent position of any object seen through it. Thus, if (fig. 455) two segments be cut from a double convex lens, and placed with their edges together, the arrows x, y, would both be seen in the position of the dotted arrow by the eyes at R and L.

If we substitute for the arrows two dissimilar pictures of the same solid object, or the same landscape, we shall then, if a diaphragm, *ab*, be placed between the lenses to prevent the pictures being seen crosswise by the eyes, see but one picture, and that apparently in the centre, and magnified. As before, if the margins are brought by the power of the lenses to coin-

cide, other corresponding points will not be coincident until combined by an almost insensible effort of the eyes. Any pair of corresponding points which are farther apart than any other pair, will then be seen farther back in the picture, just as any point in the background of a landscape would be found (if we came to compare two pictures of the landscape, one drawn by the right eye, and the other by the left) to be represented by two points farther apart from one another than two others which represented a point in the foreground.

To any one curious in such experiments, it will be instructive to notice that there is also a second point on *this side* of the paper, at which, if a person look steadily, the diagrams in fig. 456 will combine, and form quite a different stereoscopic picture. Instead of a solid pyramid, a hollow pyramidal box will then be seen. The point may easily be found by experiment. Here again two external images will also be seen. If we wish to shut these out, and see only their central stereoscopic combination, we must use a diaphragm of paper held parallel to the plane of the picture with a square hole in it. This paper screen must be so adjusted that it may conceal the right-hand figure from the left eye, and the left-hand figure from the right eye, while the central stereoscopic picture may be seen through the hole. It will be plain from the diagram that o is the point to which the eyes must be directed, and at which they will imagine the point to be situated, which is formed by the combination of the two points r and l. The dotted line shows the position of the screen. A stereoscope with or without lenses may easily be constructed, which will thus give us, with the ordinary stereoscopic slides, a reversed picture. For instance, if the subject be a landscape, the foreground will retire and the background come forward.

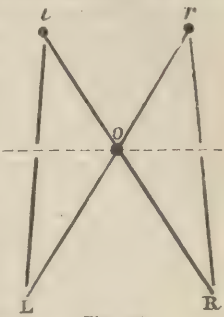


Fig. 456.

When the two retinas view simultaneously two different colours, the impression produced is that of a single mixed tint. The power, however, of combining the two tints into a single one, varies in different individuals, and in some is extremely weak. If two white discs at the base of the stereoscope be illuminated by two pencils of complementary colours, and if each coloured disc be looked at with one eye, a single white one is seen, showing that the sensation of white light may arise from two complementary and simultaneous chromatic impressions on each of the two retinas.

563. **Persistence of impression on the retina.**—When an ignited piece of charcoal is rapidly rotated, we cannot distinguish it ; the appearance of a circle of fire is produced ; similarly, rain, in falling in drops, appears in the air like a series of liquid threads. In a rapidly rotating toothed wheel the individual teeth cannot be seen. But if, during darkness, the wheel be suddenly illuminated, as by the electric spark, the individual parts may be clearly made out. These various appearances are

due to the fact that the impression of these images on the retina remains for some time after the object which has produced them has disappeared or become displaced. The duration of the persistence varies with the sensitiveness of the retina and the intensity of light. The following experiment is a further illustration of this property. A series of equal sectors are traced on a disc of glass, and they are alternately blackened; in the centre there is a pivot, on which a second disc is fixed of the same dimensions as the first, but completely blackened, with the exception of a single sector; then placing the apparatus between a window and the eye, the second disc is made to rotate. If the movement is slow, all the transparent sectors are seen, but only one at a time; by a more rapid rotation we see simultaneously two, three, or a greater number.

M. Plateau has investigated the duration of the impression by numerous similar methods, and has found that it is on the average half a second. Among many curious instances of these phenomena, the following is one of the most remarkable. If after having looked at a brightly illuminated window the eyes are suddenly closed, the image remains for a few instants, that is, a sashwork is seen consisting of luminous panes surrounded by dark frames: after a few seconds the colours become interchanged, the same framework is now seen, but the frames are now bright, and the glasses are perfectly black; this new appearance may again revert to its original appearance.

The impression of colours remains as well as that of the form of objects; for if circles divided into sectors are painted in different colours, they become confounded, and give the sensation of the colour which would result from their mixture. Yellow and red give orange; blue and red, violet; the seven colours of the spectrum give white, as shown in Newton's disc (fig. 405).

A great number of pieces of apparatus are founded on the persistence of sensation on the retina. Such are the *thaumatrope*, the *phenakistoscope*, *Faraday's wheel*, the *kaleidophone*.

564. **Accidental images.**—A coloured object being placed upon a black ground, if it is steadily looked at for some time, the eye is soon tired, and the intensity of the colour enfeebled; if now the eyes are directed towards a white sheet, or to the ceiling, an image will be seen of the same shape as the object, but of a complementary colour (501); that is, such a one as united to that of the object would form white. For a green object the image will be red; if the object is yellow the image will be violet.

Accidental colours are of longer duration in proportion as the object has been more brilliantly illuminated, and the object has been longer looked at. When a lighted candle has been looked at for some time, and the eyes are turned towards a dark part of the room, the appearance of the flame remains, but it gradually changes colour; it is first yellow, then it passes through orange to red, from red through violet to greenish blue, which is gradually feebler until it disappears. If the eye which has been looking at the light be turned towards a white wall, the colours follow almost the opposite direction: there is first a dark picture on a

white ground, which gradually changes into blue, is then successively green and yellow, and ultimately cannot be distinguished from a white ground.

The reason of this phenomenon is, doubtless, to be sought in the fact that the subsequent action of light on the retina is not of equal duration for all colours, and that the decrease in the intensity of the subsequent action does not follow the same law for all colours.

565. **Irradiation.**—This is a phenomenon in virtue of which white objects or those of a very bright colour, when seen on a dark ground, appear larger than they really are. With a black body on a bright ground, the converse is the case. Irradiation arises from the fact that the impression produced on the retina extends beyond the outline of the image. It bears the same relation to the space occupied by the image that the duration of the impression does to the time during which the image is seen.

The effect of irradiation is very perceptible in the apparent magnitude of stars, which may thus appear much larger than they really are; also in the appearance of the moon when two or three days old, the brightly illuminated crescent seeming to extend beyond the darker portion of the disc, and hold it in its grasp.

Plateau, who has investigated this subject, finds that irradiation differs very much in different people, and even in the same person it differs on different days. He has also found that irradiation increases with the lustre of the object, and the length of time during which it is viewed. It manifests itself at all distances, diverging lenses increase it, condensing lenses diminish it.

Accidental haloes are the colours which, instead of succeeding the impression of an object like accidental colours, appear round the object itself when it is looked at fixedly. The impression of the halo is the opposite to that of the object; if the object is bright the halo is dark, and *vice versâ.* These appearances are best produced in the following manner. A white surface, such as a sheet of paper, is illuminated by coloured light, and a narrow opaque body held so as to cut off some of the coloured rays. In this manner a narrow shadow is obtained which is illuminated by the surrounding white daylight, and appears complementary to the coloured ground. If red glass is used, the shadow appears green, and blue when a yellow glass is used.

The contrast of colours is a reciprocal action exerted between two adjacent colours, and in virtue of which to each one is added the complementary colour of the other. This contrast was observed by M. Chevreul, who has made it the subject of profound study. It is by the reciprocal influence of coloured shadows that the contrast of colour is explained.

M. Chevreul has found that when red and yellow colours are adjacent, red acquires a violet and orange a yellow tint. If the experiment is made with red and blue, the former acquires a yellow, and the latter a green tint: with yellow and blue, yellow passes to orange, and blue towards indigo; and so on for a vast number of combinations. The importance

of this phenomenon in its application to the manufacture of cloths, carpets, etc., may be readily conceived.

566. **The eye is not achromatic.**—It had long been supposed that the human eye was perfectly achromatic, but this is clearly impossible, as all the refractions are made the same way, viz. towards the axis ; moreover, the experiments of Wollaston, of Young, of Fraunhofer, and of Müller, have shown that it was not true in any absolute sense.

Fraunhofer showed that in a telescope with two lenses, a very fine wire placed inside the instrument in the focus of the object glass is seen distinctly through the eye-piece, when the telescope is illuminated with red light ; but it is invisible by violet light even when the eye-piece is in the same position. In order to see the wire again, the distance of the lenses must be diminished to a far greater extent than would correspond to the degree of refrangibility of violet light in glass. In this case, therefore, the effect must be due to a chromatic aberration in the eye.

Müller, on looking at a white disc on a dark ground, found that the image is sharp when the eye is accommodated to the distance of the disc, that is, when the image forms on the retina ; but he found that if the image is formed in front of or behind the retina, the disc appears surrounded by a very narrow blue edge.

If a finger be held up in front of one eye (the other being closed) in such a manner as to allow the light to enter only one-half of the pupil, and, of course, obliquely, and the eye be then directed to any well-defined line of light, such as a slit in the shutter of a darkened room, or a strip of white paper on a black ground, this line of light will appear as a complete spectrum.

Müller concluded from these experiments that the eye is sensibly achromatic as long as the image is received at the focal distance, or when it is accommodated to the distance of the object. The cause of this apparent achromatism cannot be exactly stated. It has generally been attributed to the tenuity of the luminous beams which pass through the pupillary aperture, and that these unequally refrangible rays, meeting the surfaces of the media of the eye almost at the normal incidence, are very little refracted, from which it follows that the chromatic aberration is imperceptible (520).

As to the spherical aberration, we have already seen how this is corrected by the iris (549). The iris is in point of fact a diaphragm, which arrests the marginal rays, and only allows those to pass which are near the axis.

567. **Short sight and long sight ; myopy and presbytism.**—The most usual affections of the eye are *myopy* and *presbytism*, or *short sight* and *long sight*. Short sight is the habitual accommodation of the eyes for a distance less than that of ordinary vision, so that persons affected in this way only see very near objects distinctly. The usual cause of short sight is a too great convexity of the cornea or of the crystalline ; the eye being then too convergent, the focus, in place of forming on the retina, is formed in front, so that the image is indistinct. It may be remedied by means of diverging glasses, which in making the rays deviate from their

common axis throw the focus farther back, and cause the image to be formed on the retina.

The habitual contemplation of small objects, as when children are too much accustomed, in reading and writing, to place the paper close to their eyes, or working with a microscope, may produce short sight. It is common in the case of young people, but diminishes with age.

Long sight is the contrary of short sight : the eye can see distant objects very well, but cannot distinguish those which are very near. The cause of long sight is that the eye is not sufficiently convergent, and hence the image of objects is formed beyond the retina : but if the objects are removed farther off, the image approaches the retina, and when they are at a suitable distance is exactly formed upon it, so that the object is clearly seen.

Long sight is corrected by means of converging lenses. These glasses bring the rays together before their entrance into the eye, and, therefore, if the converging power is properly chosen, the image will be formed exactly on the retina.

It is not many years since double convex lenses were alone used for long-sighted persons, and double concave for short-sighted persons. Wollaston first proposed to replace these glasses by concavo-convex lenses, C and F (fig. 382), so placed that their curvature is in the same direction as that of the eye. By means of these glasses a much wider range is attained, and hence they have been called *periscopic glasses.*

568. **Eye-glasses. Spectacles.**—The glasses commonly used by short or long sighted persons are known under the general name of eye-glasses, or spectacles. Generally speaking, numbers are engraved on these glasses which express their focal length in *inches.*

The number which a short or long sighted person ought to use may be calculated, knowing the distance of distinct vision. The formula

$$f=\frac{pd}{d-p} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

serves for long-sighted persons, where f being the number which ought to be taken, p is the distance of distinct vision in ordinary cases (about 12 inches), and d the distance of distinct vision for the person affected by long sight.

The above formula is obtained from the equation $\frac{1}{p}-\frac{1}{p'}=\frac{1}{f}$ by substituting d for p'. In this case the formula (6) of article 505 is used, and not formula (5), because the image seen by spectacles being on the same side of the object in reference to the lens, the sign of p' ought to be the opposite of that of p, as in the case of virtual images from the paragraph already cited.

For short-sighted persons, f is calculated by the formula $\frac{1}{p}-\frac{1}{p'}=-\frac{1}{f}$ (505), which belongs to concave lenses, and which, replacing p' by d, gives

$$f=\frac{pd}{p-d} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

To calculate, for instance, the number of a glass which a person ought to use in whom the distance of distinct vision is 36, knowing that the distance of ordinary distinct vision is 12 inches. Making $p = 12$ and $d = 36$ in the above formula (1), we get $f = \frac{36 \times 12}{36 - 12} = 18$.

569. **Diplopy.**—Diplopy is an affection of the eye which causes objects to be seen double, that is, that two images are seen instead of one. Usually the two images are almost entirely superposed, and one of them is much more distinct than the other. Diplopy may be caused by the co-operation of two unequal eyes, but it may also affect a single eye. The latter case is, doubtless, due to some defect of conformation in the crystalline or other parts of the eye which produces a bifurcation of the luminous ray, and thus two images are formed on the retina instead of one. A single eye may also be affected with triplopy, but in this case the third image is exceedingly weak.

570. **Achromatopsy : Daltonism.**—*Achromatopsy*, or *colour disease*, is a curious affection which renders us incapable of distinguishing colours, or at any rate certain colours. In some cases the insensibility is complete, while in others some colours can be very well distinguished. Persons affected in this manner can distinguish the outlines of bodies without difficulty, and they can also discriminate between light and shade, but they are unable to distinguish the different tints.

D'Hombres-Firmas cites an instance of a person affected with achromatopsy, who had painted in a room a landscape of which the ground, trees, houses, and men were all painted blue, and when asked why he had not given each its proper colour, he replied that he wished to assimilate the colour of his drawing to that of his furniture ; now this was red.

Achromatopsy is also sometimes called *Daltonism*, because Dalton, who has carefully described it, was so affected.

571. **Ophthalmoscope.**—This instrument, as its name indicates, is designed for the examination of the eye, and was invented in 1851 by Prof. Helmholz. It consists :—1. Of a concave spherical reflector of glass or metal, M (figs. 457, 458), in the middle of which is a small hole about a sixth of an inch in diameter. The focal length of the reflector is from 8 to 10 inches. 2. Of a converging achromatic lens, *o*, which is held in front of the eye of the patient. 3. Of several lenses, some convergent, others divergent, any one of which can be fixed in a frame behind the mirror so as to correct any given imperfection in the observer's sight. If the mirror is of silvered glass, it is not necessary that it be pierced at the centre ; it is sufficient that the silvering at the centre be removed.

To make use of the ophthalmoscope, the patient is placed in a darkened room, and a lamp furnished with a screen put beside him, E. The screen serves to shade the light from his head, and keep it in darkness. The observer A, holding in one hand the reflector, employs it to concentrate the light of the lamp near the eye B of the patient, and with his other hand holds the achromatic lens *o* in front of the eye. By this arrange-

ment the back of the eye is lighted up, and its structure can be clearly discerned.

Fig. 458 shows how the image of the back of the eye is produced, which

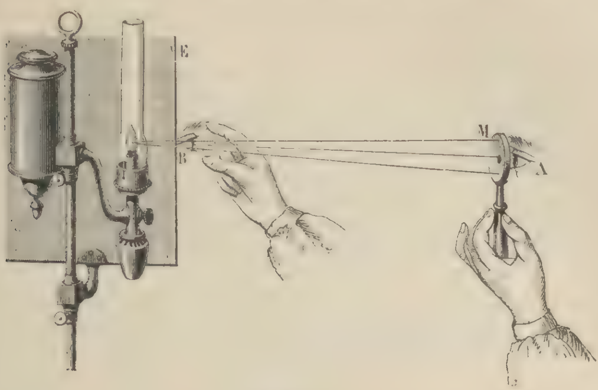


Fig. 457.

the observer A sees on looking through the hole in the reflector. Let *ab* be the part of the retina on which the light is concentrated, pencils of rays proceeding from *ab* would form an inverted and aërial image of *ab* at *a′b′*. These pencils, however, on leaving the eye, pass through the lens *o*, and

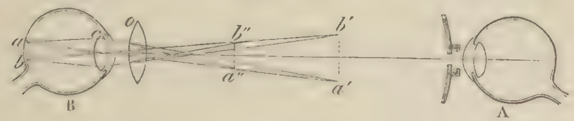


Fig. 458.

thus the image *a″b″* is in fact formed, inverted, but distinct, and in a position fit for vision.

The great quantity of light concentrated by the ophthalmoscope is apt to irritate painfully the eye of the patient. There are therefore interposed between the lamp and the reflector coloured glasses, to cut off the irritating rays, viz., the red, yellow, and violet rays. The glasses generally employed are stained green or cobalt-blue.

CHAPTER VII.

SOURCES OF LIGHT. PHOSPHORESCENCE.

572. **Various sources of light.**—The various sources of light are the sun, the stars, heat, chemical combination, phosphorescence, electricity, and meteoric phenomena. The last two sources will be treated under the articles *Electricity* and *Meteorology*.

The origin of the light emitted by the sun and by the stars is unknown: it is assumed that the ignited envelope by which the sun is surrounded is gaseous, because the light of the sun, like that emitted from all gaseous bodies, gives no trace of polarisation in the polarising telescope (Chapter VIII.).

As regards the light developed by heat, Pouillet has observed that bodies begin to be luminous in the dark at a temperature of 500° to 600°; above that the light is brighter in proportion as the temperature is higher.

The luminous effects witnessed in many chemical combinations are due to the high temperatures produced. This is the case with the artificial lights used for illuminations; for as we have already seen, luminous flames are nothing more than gaseous matters containing solids heated to the point of incandescence.

573. **Phosphorescence: its sources.**—*Phosphorescence* is the property which a large number of substances possess of emitting light when placed under certain conditions.

M. Becquerel, who has studied this subject in a very comprehensive manner, and has arrived at some extremely remarkable results, refers the phenomena to five causes:

i. *Spontaneous phosphorescence* in certain vegetables and animals; for instance, it is very intense in the glow-worm and in the lampyre, and the brightness of their light appears to depend on their will. In tropical climates the sea is often covered with a bright phosphorescent light due to some extremely small zoophytes. These animalculæ emit a luminous matter so subtile that MM. Quoy and Gaimard, during a voyage under the equator, having placed two in a tumbler of water, the liquid immediately became luminous throughout its entire mass.

ii. *Phosphorescence by elevation of temperature.* This is best seen in certain species of diamonds and in fluorspar, which, when heated to 300° or 400°, suddenly become luminous, emitting a bluish light.

iii. *Phosphorescence by mechanical effects*, such as friction, percussion, cleavage, etc.; for example, when two crystals of quartz are rubbed against each other in darkness, or when a lump of sugar is broken.

iv. *Phosphorescence by electricity*, like that which results from the friction of mercury against the glass in a barometric tube, and especially from the electric sparks proceeding either from an ordinary electrical machine, or from a Ruhmkorff's coil.

v. *Phosphorescence by insolation or exposure to the sun.* A large number of substances, after having been exposed to the action of solar light, or of the diffused light of the atmosphere, emit in darkness a phosphorescence, the colour and intensity of which depend on the nature and physical condition of these substances. It is this kind of phosphorescence which has been studied by M. Becquerel, an abstract of whose researches is given in the next paragraph.

574. **Phosphorescence by insolation.**—This was first observed in 1604 in Bolognese phosphorus (sulphide of barium), but M. Ed. Becquerel has also discovered it in a great number of substances. The sulphides of calcium and strontium are those which present it in the highest degree. When well prepared, after being exposed to the light, they are luminous for several hours in darkness. But as this phosphorescence takes place in vacuo as well as in a gaseous medium, it cannot be attributed to a chemical action, but rather to a temporary modification which the body undergoes from the action of light.

After the substances above named, the best phosphorescents are the following, in the order in which they are placed: a large number of diamonds (especially yellow), and most specimens of fluorspar; then arragonite, calcareous concretions, chalk, apatite, heavy spar, dried nitrate of calcium, and dried chloride of calcium, cyanide of calcium, a large number of strontium or barium compounds, magnesium and its carbonate, etc. Besides these a large number of organic substances also become phosphorescent by insolation; for instance, dry paper, silk, cane-sugar, milk-sugar, amber, the teeth, etc.

Becquerel finds that the different spectral rays are not equally well fitted to render substances phosphorescent. The maximum effect takes place in the violet rays, or even a little beyond; while the light emitted by phosphorescent bodies generally corresponds to rays of a smaller refrangibility than those of the light received by them, and giving rise to the action.

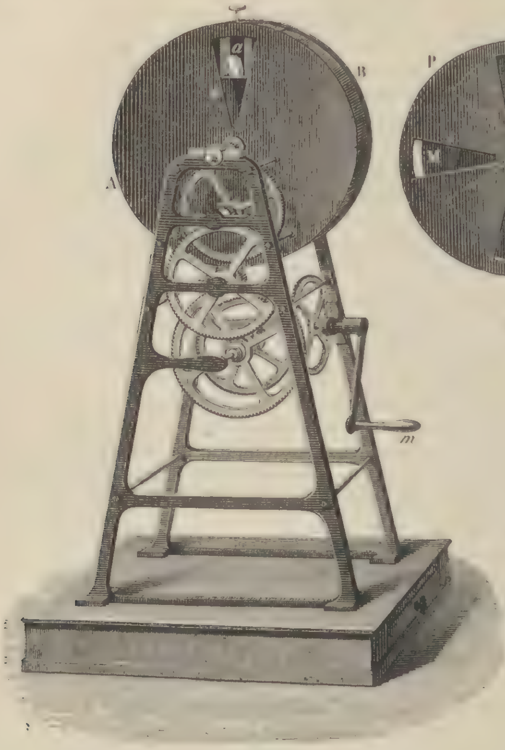
The tint which phosphorescent bodies assume is very variable, and even in the same body it changes with the manner in which it is prepared. In strontium compounds green and blue tints predominate; and orange, yellow, and green tints in the sulphides of barium.

The duration of phosphorescence varies also in different bodies. In the sulphides of calcium and strontium phosphorescence lasts as much as thirty hours; with other substances it does not exceed a few seconds, or even a fraction of a second.

Phosphoroscope. In experimenting with bodies whose phosphorescence lasts a few minutes or even a few seconds, it is simply necessary to expose them to solar or diffused light for a short time, and then place them in darkness: their luminosity is very apparent, especially if care has previously been taken to close the eyes for a few instants. But in the case of bodies whose phosphorescence lasts only a very short time, this method is inadequate. M. Becquerel has invented a very ingenious apparatus, the *phosphoroscope*, by which bodies can be viewed immediately after being exposed to light: the interval which separates the insolation

and observation can be made as small as possible, and measured with great precision.

This apparatus, which is constructed by M. Duboscq, consists of a



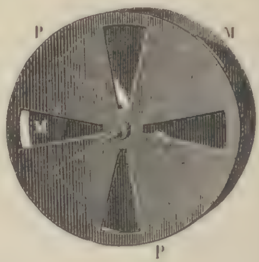


Fig. 460.

Fig. 459

closed cylindrical box, AB (fig. 459), of blackened metal; on the ends there are two apertures opposite each other which have the form of a circular sector. Only one of these, *o*, is seen in the figure. The box is fixed, but it is traversed in the centre by a movable axis, to which are fixed two circular screens, MM and PP, of blackened metal (fig. 460). Each of these screens is perforated by four apertures of the same shape as those in the box; but while the latter correspond to each other, the apertures of the screens alternate, so that the open parts of the one correspond to the closed parts of the other. The two screens, as already mentioned, are placed in the box, and fixed to the axis, which by means of a train of wheels, worked by a handle, can be made to turn with any velocity.

In order to investigate the phosphorescence of any body by means of

this instrument, the body is placed on a stirrup interposed between the two rotating screens. The light cannot pass at the same time through the opposite apertures of the sides A and B, because one of the closed parts of the screen MM, or of the screen PP, is always between them. So that when a body, *a*, is illuminated by light from the other side of the apparatus, it could not be seen by an observer looking at the aperture *o*, for then it would be masked by the screen PP. Accordingly, when an observer saw the body *a*, it would not be illuminated, as the light would be intercepted by the closed parts of the screen MM. The body *a* would alternately appear and disappear; it would disappear during the time of its being illuminated, and appear when it was no longer so. The time which elapses between the appearance and disappearance depends on the velocity of rotation of the screens. Suppose, for instance, that they made 150 turns in a second; as one revolution of the screens is effected in $\frac{1}{150}$ of a second, there would be four appearances and four disappearances during that time. Hence the length of time elapsing between the time of illumination and of observation would be $\frac{1}{8}$ of $\frac{1}{150}$ of a second or 0·0008 of a second.

Observations with the phosphoroscope are made in a dark chamber, the observer being on that side on which is the wheelwork. A ray of solar or of electric light is allowed to fall upon the substance *a*, and the screens being made to rotate more or less rapidly, the body *a* appears luminous by transparence in a continuous manner, when the interval between insolation and observation is less than the duration of the phosphorescence of the body. By experiments of this kind, Becquerel has found that substances which usually are not phosphorescent become so in the phosphoroscope; such, for instance, is Iceland spar. Uranium compounds present the most brilliant appearance in this apparatus; they emit a very bright luminosity when the observer can see them 0·003 or 0·004 of a second after insolation. But a large number of bodies present no effect in the phosphoroscope; for instance, quartz, sulphur, phosphorus, metals, and liquids.

CHAPTER VIII.

DOUBLE REFRACTION. INTERFERENCE. POLARISATION.

575. **The undulatory theory of light.**—It has been already stated (452) that the phenomenon of light is, with good reason, ascribed to undulations propagated through an exceedingly rare medium called the luminiferous ether, which is supposed to pervade all space, and to exist between the molecules of the ordinary forms of matter. In a word, it is held that light is due to the undulations of the ether, just as sound is due to undulations propagated through the air. In the latter case the

undulations cause the drum of the ear to vibrate and produce the sensation of sound. In the former case the undulations cause points of the retina to vibrate and produce the sensation of light. The two cases differ in this, that in the case of sound there is independent evidence of the existence and vibration of the medium (air) which propagates the undulation, whereas in the case of light the existence of the medium and its vibrations are *assumed*, because that supposition connects and explains in the most complete manner a long series of very various phenomena. There is, however, no independent evidence of the existence of the luminiferous ether.

The analogy between the phenomena of sound and light is very close; thus, the intensity of a sound is greater as the amplitude of the vibration of each particle of the air is greater, and the intensity of light is greater as the amplitude of the vibration of each particle of the ether is greater. Again, a sound is more acute as the length of each undulation producing the sound is less, or, which comes to the same thing, according as the number of vibrations per minute is greater. In like manner, the colour of light is different according to the length of the undulation producing the light; a red light is due to a comparatively long undulation, and corresponds to a deep sound, while a violet light is due to a short undulation, and corresponds to an acute sound.

Although the length of the undulations cannot be observed directly, yet they can be inferred from certain phenomena with great exactness. The following table gives the length of the undulations corresponding to the light at the principal dark lines of the spectrum. The lengths are given in decimals of an inch.

Dark Line	Length of Undulation
B	0·0000271
C	0·0000258
D	0·0000244
E	0·0000207
F	0·0000191
G	0·0000169
H	0·0000155

It will be remarked that the limits are very narrow within which the lengths of the undulations of the ether must be comprised, if they are to be capable of producing the sensation of light. In this respect light is in marked contrast to sound. For the limits are very wide within which the lengths of the undulations of the air may be comprised when they produce the sensation of sound (224).

The undulatory theory readily explains the colours of different bodies. According to that theory, certain bodies have the property of exciting undulations of different lengths, and thus producing light of given colours. White light or daylight results from the coexistence of undulations of all possible lengths.

The colour of a body is due to the power it has of extinguishing certain

vibrations, and reflecting others; and the body appears of the colour produced by the coexistence of the reflected vibrations. A body appears white when it reflects all different vibrations in the proportion in which they are present in the spectrum : it appears black when it reflects light in such small quantities as not to affect the eye. A red body is one which has the property of reflecting in predominant strength those vibrations which produce the sensation of red. This is seen in the fact that, when a piece of red paper is held against the daylight, and the reflected light is caught on a white wall, this also appears red. A piece of red paper in the red part of the spectrum appears of a brighter red, and a piece of blue paper held in the blue part appears of a brighter blue; while a red paper placed in the violet or blue part appears almost black. In the last case the red paper can only reflect red rays, while it extinguishes the blue rays, and as the blue of the spectrum is almost free from red, so little is reflected that the paper appears black.

The undulatory theory likewise explains the colours of transparent bodies. Thus, a vibrating motion on reaching a body sets it in vibration. So also the vibrations of the luminiferous ether are communicated to the ether in a body, and setting it in motion produce light of different colours. When this motion is transmitted through any body, it is said to be *transparent* or *translucent*, according to the different degrees of strength with which this transmission is effected. In the opposite case it is said to be *opaque*.

When light falls upon a transparent body, the body appears colourless if all the vibrations are transmitted in the proportion in which they exist in the spectrum. But if some of the vibrations are checked or extinguished, the emergent light will be of the colour produced by the coexistence of the unchecked vibrations. Thus, when a piece of blue glass is held before the eye, the vibrations producing red and yellow are extinguished, and the colour is due to the emergent vibrations which produce blue light.

The undulatory theory also accounts for the reflection and refraction of light, as well as other phenomena which are yet to be described. The explanation of the refraction of light is of so much importance that we shall devote to it the following article.

576. **Physical explanation of single refraction.**—The explanation of this phenomenon by means of the undulatory theory of light presupposes that of the mode of propagation of a plane wave. Now, if a disturbance originated at any *point* of the ether, it would be propagated as a spherical wave in all directions round that point with a uniform velocity. If, instead of a single point, we consider the front of a plane wave, it is evident that disturbances originate simultaneously at all points of that front, and that spherical waves proceed from each *point* with the same uniform velocity. Consequently all these spheres will at any subsequent instant be touched by a plane parallel to the original plane. The disturbances propagated from the points in the first position of the wave will mutually destroy each other, except in the tangent plane; consequently the wave advances as a plane wave, its successive positions being the

successive positions of the tangent plane. If the wave moves in the medium with a velocity v, it will describe a space vt in a time t.

Suppose the plane wave, AC (fig. 461), to move through vacuum and to meet the plane surface, AB, of an ordinary refracting medium at an

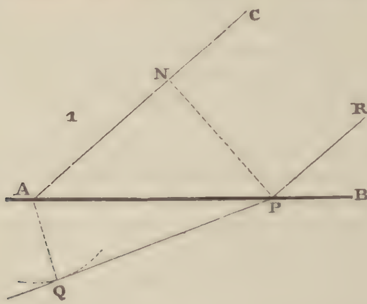


Fig. 461.

angle CAB or I. Suppose the velocity of propagation in vacuo to be v, and in the medium to be v'. Now the wave entering the medium at A will after any time (t) be moving partly within and partly without the medium. Suppose PR to be the part outside the medium, draw PN at right angles to AC, then PN equals vt. Now in the same time, t, a spherical wave propagated from A, will have a radius $v't$; if, then, PQ is drawn touching a circle whose centre is A and whose radius AQ equals $v't$, then PQ will be the position of the plane wave within the medium at the instant under consideration. If we denote the angle APQ by R it is plain that

$$\text{Sin I} : \sin \text{R} :: \text{PN} : \text{AQ} :: vt : v't :: v : v'.$$

But a succession of parallel plane waves will give rise to a pencil of parallel rays at right angles to the waves; consequently, with respect to any one of these rays, I and R are the angles of incidence and refraction. Therefore the ratio of the sines of those angles is constant and equals $v : v'$, which is the distinctive law of single refraction.

Moreover, if μ is the refractive index of the substance, $v \div v'$ equals μ, that is, v equals $v' \mu$. Now, under all circumstances, μ is greater than 1, and therefore v is greater than v', a result which coincides with that obtained from experiment (459).

DOUBLE REFRACTION.

577. **Double refraction.**—It has been already stated (483) that a large number of crystals possess the property of double refraction, in virtue of which a single incident ray in passing through any one of them is divided into two, or undergoes *bifurcation.* Whence it follows that, when an object is seen through one of these crystals, it appears double. The fact of the existence of double refraction in Iceland spar was first stated by

Bartholin in 1669, but the law of double refraction was first enunciated exactly by Huyghens in his treatise on light written in 1678, and published in 1690.

Crystals which possess this peculiarity are said to be *double refracting*. It is found to a greater or less extent in all crystals which do not belong to the cubical system. Bodies which crystallise in this system, and those which, like glass, are destitute of crystallisation, have no double refraction. The property can, however, be imparted to them when they are unequally compressed, or when they are cooled quickly after having been heated, in which state glass is said to be unannealed. Of all substances, that which possesses it most remarkably is Iceland spar or carbonate of calcium. In many substances the power of double refraction can hardly be proved to exist directly by the bifurcation of an incident ray; but its existence is shown indirectly by their being able to 'depolarise' light.

Fresnel has explained double refraction by assuming that the ether in double refracting bodies is not equally elastic in all directions; from which it follows that the vibrations in certain directions at right angles to each other are transmitted with unequal velocities; these directions being dependent on the constitution of the crystal. This hypothesis is confirmed by the property which glass acquires of becoming double refracting by being unannealed and by pressure.

578. **Uniaxial crystals.**—In all double refracting crystals there is *one* direction, and in some a second direction possessing the following property. When a point is looked at through the crystal in this particular direction, it does *not* appear double. The lines fixing these directions are called *optic axes*; and sometimes, though not very properly, axes of double refraction. A crystal is called *uniaxial* when it has *one* optic axis, that is to say, when there is one direction within the crystal along which a ray of light can proceed without bifurcation. When a crystal has two such axes, it is called a biaxial crystal.

The uniaxial crystals most frequently used in optical instruments are Iceland spar, quartz, and tourmaline. Iceland spar crystallises in rhombohedra, whose faces form with each other angles of 105° 5′ or 74° 55′. It has eight solid angles (see fig. 462). Of these two, situated at the extremities of one of the diagonals, are severally contained by three obtuse angles. A line drawn within one of these two angles in such a manner as to be equally inclined to the three edges containing the angle is called the *axis of the crystal*. If all the edges of the crystal were equal, the axis of the crystal would coincide with the diagonal, *ab*.

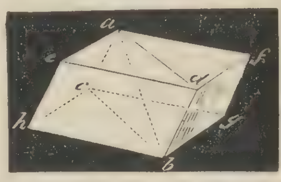


Fig. 462.

Brewster has shown that in all uniaxial crystals the optic axis coincides with the axis of crystallisation.

The principal plane with reference to a point of any face of a crystal, whether natural or artificial, is a plane drawn through the point at right angles to the face and parallel to the optic axis. If in fig. 462 we suppose

the edges of the rhombohedron to be equal, the diagonal plane *abcd* contains the optic axis (*ab*), and is at right angles to the faces *acdf* and *chbg*; consequently it is parallel to the principal plane at any point of either of those two faces. For this reason *acbd* is often called the principal plane with respect to those faces.

579. **Ordinary and extraordinary ray.**—Of the two rays into which an incident ray is divided on entering a uniaxial crystal, one is called the *ordinary* and the other the *extraordinary* ray. The ordinary ray follows the laws of single refraction, that is, with respect to that ray the sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction, and the plane of incidence coincides with the plane of refraction. Except in particular positions the extraordinary ray follows neither of these laws. The images corresponding to the ordinary and extraordinary rays are called the ordinary and extraordinary images respectively.

If a transparent specimen of Iceland spar be placed over a dot of ink, on a sheet of white paper, the two images will be seen. One of them, the ordinary image, will seem slightly nearer to the eye than the other, the extraordinary image. Suppose the spectator to view the dot in a direction at right angles to the paper, then, if the crystal, with the face still on the paper, be turned round, the *ordinary* image will continue fixed, and the extraordinary image will describe a circle round it, the line joining them being always in the direction of the shorter diagonal of the face of the crystal, supposing its edges to be of equal length. In this case it is found that the angle between the ordinary and extraordinary ray is 6° 12′.

580. **The laws of double refraction in a uniaxial crystal.**—These phenomena are found to obey the following laws:—

i. Whatever be the plane of incidence, the ordinary ray always obeys the two general laws of single refraction (484). The refractive index for the ordinary ray is called the ordinary refractive index.

ii. In every section perpendicular to the optic axis the extraordinary ray also follows the laws of single refraction. Consequently in this plane the extraordinary ray has a constant refractive index, which is called the extraordinary refractive index.

iii. In every principal section the extraordinary ray follows the second law only of single refraction, that is, the planes of incidence and refraction coincide, but the ratio of the sines of the angles of incidence and refraction is not constant.

iv. The velocities of light along the rays are unequal. It can be shown that the difference between the squares of the reciprocals of the velocities along the ordinary and extraordinary rays is proportional to the square of the sine of the angle between the latter ray and the axis of the crystal.

There is an important difference between the velocity of the *ray* and the velocity of the corresponding *plane wave*. If the velocities of the plane waves corresponding to the ordinary and extraordinary rays are considered, the difference between the squares of these velocities is proportional to the square of the sine of the angle between the axis of the crystal and the normal to that plane wave which corresponds to the extraordinary ray. The normal and the ray do not generally coincide.

Huyghens gave a very remarkable geometrical construction, by means of which the directions of the refracted rays can be determined when the directions of the incident ray and of the axis are known relatively to the face of the crystal. This construction was not generally accepted by physicists until Wollaston and subsequently Malus showed its truth by numerous exact measurements.

581. **Positive and negative uniaxial crystal.** — The term extraordinary refractive index has been defined in the last article. For the same crystal its magnitude always differs from that of the *ordinary* refractive index; for example, in Iceland spar the ordinary refractive index is 1·654, while the extraordinary refractive index is 1·483. In this case the ordinary index exceeds the extraordinary index. When this is the case, the crystal is said to be negative. On the other hand, when the extraordinary index exceeds the ordinary index, the crystal is said to be positive. The following list gives the names of some of the principal uniaxial crystals:—

Negative Uniaxial Crystals.

Iceland spar	Emerald
Spathose Iron	Apatite
Tourmaline	Pyromorphite
Sapphire	Ferrocyanide of potassium
Ruby	Nitrate of sodium

Positive Uniaxial Crystals.

Zircon	Ice
Quartz	Titanite
Apophyllite	Boracite

582. **Double refraction in biaxial crystals.** — A large number of crystals, including all those belonging to the *trimetric*, the *monoclinic*, and the *triclinic* systems, possess two *optic axes*; in other words, in each of these crystals there are two directions along which a ray of light passes without bifurcation. A line bisecting the acute angle between the optic axes is called the medial line; one that bisects the obtuse angle is called the supplementary line. It has been found that the medial and supplementary lines and a third line at right angles to both are closely related to the fundamental form of the crystal to which the optic axes belong. The acute angle between the optic axes is different in different crystals. The following table gives the magnitude of this angle in the case of certain crystals:—

Nitre	5° 20′	Anhydrite	28° 7′
Strontianite	6 56	Heavy spar	37 42
Arragonite	18 18	Mica	45 0
Brazilian topaz	49 50	Kyanite	81 48
Sugar	50 0	Epidote	84 19
Selenite	60 0	Sulphate of iron	90 0

When a ray of light enters a biaxial crystal, and passes in any direction not coinciding with an optic axis, it undergoes bifurcation; in this case,

however, neither ray conforms to the laws of single refraction, but both are extraordinary rays. To this general statement the following exception must be made. In a section of a crystal at right angles to the medial line one ray follows the laws of ordinary refraction, and in a section at right angles to the supplementary line the other ray follows the laws of ordinary refraction.

INTERFERENCE AND DIFFRACTION.

583. **Interference of light.**—The name *interference* is given to the mutual action which two luminous rays exert upon each other when they are emitted from two neighbouring sources, and meet each other under a very small angle. This action may be observed by means of the following experiment. In the shutter of a dark room two very small apertures are made, of the same diameter, at a very slight distance from each other. The apertures are closed by pieces of coloured glass—red, for example—by which two pencils of homogeneous light are introduced. These two pencils form two divergent luminous cones, which meet at a certain distance; they are received on a white screen a little beyond the place at which they meet, and in the segment common to the two discs which form upon this screen some very well-defined alternations of red and black bands are seen. If one of the two apertures be closed, the fringes disappear, and are replaced by an almost uniform red tint. From the fact that the dark fringes disappear when one of the beams is intercepted, it is concluded that they arise from the interference of the two pencils which cross obliquely.

This experiment was first made by Grimaldi, but was modified by Young. Grimaldi had drawn from it the conclusion that light added to light produced darkness. The full importance of this principle remained for a long time unrecognised, until these enquiries were resumed by Young and Fresnel, of whom the latter, by a modification of Grimaldi's experiment, rendered it an *experimentum crucis* of the truth of the undulatory hypothesis.

In Grimaldi's experiment diffraction (584) takes place; for the luminous rays pass by the edge of the aperture. In Fresnel's experiment the two pencils interfere without the possibility of diffraction.

Two plane mirrors, AB and BC (fig. 463), of metal, are arranged close to each other, so as to form a very obtuse angle, ABC, which must be very little less than 180°. A pencil of red light, which passes into the dark chamber, is brought, by means of a lens, L, to a focus F. On diverging from F the rays fall partly on AB, and partly on BC. If BA is produced to P and FPF_1 is drawn at right angles to AP, and if PF_1 is made equal to PF, then the rays which fall on AB will, after reflection, proceed as if they diverged from F_1. If a similar construction is made for the rays falling on BC, they will proceed after reflection as if they diverged from F_2. A little consideration will show that F_1 and F_2 are very near each other. Suppose the reflected rays to fall on a screen SS_1 placed nearly at right angles to their directions. Every point of the

screen which receives light from both pencils is illuminated by two rays, viz. one from F_1, the other from F_2; thus the point H is illuminated by

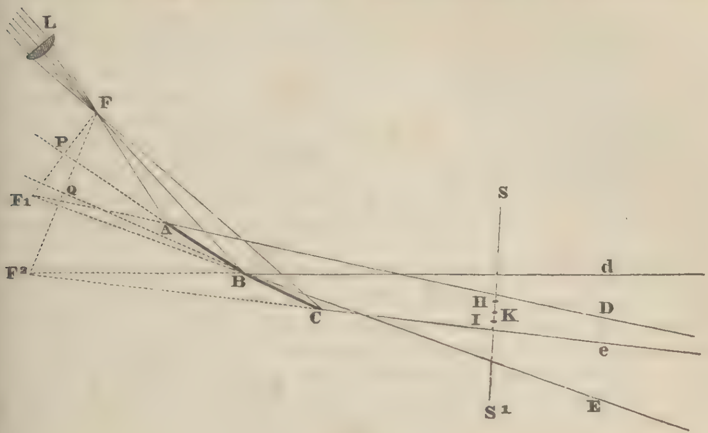


Fig. 463.

two rays, as also are K and I. Now the combined action of these two pencils is to form a series of parallel bands alternately light and dark on the screen at right angles to the plane of the paper. This is the fundamental phenomenon of interference, and that it results from the *joint action of the two pencils* is plain, since, if the light which falls upon either of the mirrors is cut off, the dark bands disappear.

This remarkable fact is explained in the most satisfactory manner by the undulatory theory of light. The explanation exactly resembles that already given of the formation of nodes and loops by the combined action of two aërial waves (246); the only difference being that in that case the vibrating particles were supposed to be particles of air, whereas, in the present case, the vibrating particles are supposed to be those of the luminiferous ether. Consider any point K on the screen, and first let us suppose the distances of K from F_1 and F_2 to be equal. Then the undulations which reach K will always be in the same *phase*, and the particle of ether at K will vibrate as if the light came from one source; the amplitude of the vibration, however, will be increased in exactly the same manner as happens at a loop or ventral point; consequently at K the intensity of the light will be increased. And the same will be true for all points on the screen, such that the difference between their distances from the two images equals the length of *one*, *two*, *three*, etc., undulations. If, on the other hand, the distances of K from F_1 and F_2 differ by the length of half an undulation, then the two waves would reach K in exactly opposite phases. Consequently, whatever velocity would be communicated at any instant to a particle of ether by the one undulation, an exactly equal and opposite velocity would be commu-

nicated by the other undulation, and the particle would be *permanently* at rest, or there would be darkness at that point; this result being produced in a manner precisely resembling the formation of a *nodal* point already explained. The same will be true for all positions of K, such that the differences between its distances from F_1 and F_2 equal three halves, or five halves, or seven halves, etc., of an undulation. Accordingly, there will be on the screen a succession of alternations of light and dark points, or rather lines—for what is true of points in the plane of the paper (fig. 463) will be equally true of other points on the screen which is supposed to be at right angles to the plane of the paper. Between the light and dark lines the intensity of the light will vary, increasing gradually from darkness to its greatest intensity, and then decreasing to the second dark line, and so on.

If instead of red light any other coloured light were used, for example violet light, an exactly similar phenomenon would be produced, but the distance from one dark line to another would be different. If white light were used, each separate colour tends to produce a different set of dark lines. Now these sets being superimposed on each other, and not coinciding, the dark lines due to one colour are illuminated by other colours, and instead of dark lines a succession of coloured bands is produced. The number of coloured bands produced by white light is much smaller

Fig. 464.

than the number of dark lines produced by a homogeneous light; since at a small distance from the middle band the various colours are completely blended, and a uniform white light produced.

584. **Diffraction and fringes.**—Diffraction is a modification which light undergoes when it passes the edge of a body, or when it traverses a small aperture; a modification in virtue of which the luminous rays appear to become bent, and to penetrate into the shadow.

This phenomenon may be observed in the following manner: A beam of solar light is allowed to pass through a very small aperture in the shutter of a dark room, where it is received on a condensing lens, L (fig. 464), with a short focal length. A red glass is placed in the aperture so as only to allow red light to pass. An opaque screen, *e*, with a sharp edge, is placed behind the lens beyond its focus, and intercepts one portion of the luminous cone, while the other is projected on the screen *b*, of which B represents a front view. The following phenomena are now seen: Within the geometrical shadow, the limit of which is represented by the line *ab*, a faint light is seen, which gradually fades in proportion as it is farther from the limits of the shadow. In that part of the screen which, being above the line *ab*, might be expected to be uniformly illu-

minated, a series of alternate dark and light bands or fringes are seen parallel to the line of shadow, which gradually becomes more indistinct and ultimately disappear. The limits between the light and dark fringes are not quite sharp lines ; there are parts of maximum and minimum intensity which gradually fade off into each other.

All the colours of the spectrum give rise to the same phenomenon, but the fringes are broader in proportion as the light is less refrangible. Thus, with red light they are broader than with green, and with green than with violet. Hence, with white light, which is composed of different colours, the dark spaces of one tint overlap the light spaces of another, and thus a series of prismatic colours will be produced.

If, instead of placing the edge of an opaque body between the light and the screen, a very narrow body be interposed, such as a hair or a fine metallic wire, the phenomena will be different. Outside the space corresponding to the geometrical shadow, there is a series of fringes, as in the former case. But within the shadow also there is a series of alternate light and dark bands. They are called interior fringes, and are much narrower and more numerous than the external fringes.

When a small opaque circular disc is interposed, its shadow on the screen shows in the middle a bright spot surrounded by a series of coloured concentric rings ; the bright spot is of various colours according to the relative positions of the disc and screen. The haloes sometimes seen round the sun and moon belong to this class of phenomena. They are due, as Fraunhofer has shown, to the diffraction of light by small globules of fog in the atmosphere. Fraunhofer has even given a method of estimating the mean diameter of these globules from the dimensions of the haloes. A beautiful phenomenon of the same kind is produced by looking at a flame through lycopodium powder strewed on glass.

585. **Gratings.**—Phenomena of diffraction of another class are produced by allowing the pencil of light from the luminous point to traverse an aperture in an opaque screen. The diffracted light may be received on a sheet of white paper, but the images are much better seen through a small telescope placed behind the aperture. If the aperture is very small, the telescope may be dispensed with, and the figure may be viewed by placing the aperture before the eye.

Some of the simpler apertures, such as straight lines, triangles, squares, or circles, may be cut out of tinfoil pasted on glass. Gratings may be obtained either by a series of fine equidistant wires, or by careful ruling on a piece of smoked glass ; and apertures of any form may be produced with great accuracy by taking on glass a collodion picture of a sheet of paper on which the required forms are drawn in black.

Looking through any of these apertures, we see the luminous point surrounded with coloured spectra of very various forms, and of great beauty.

The beautiful colours seen on looking through a bird's feather at a distant source of light, and the colours of striated surfaces, such as mother-of-pearl, are due to a similar cause.

The whole of these phenomena are in exact accordance with the undulatory theory, but the explanation is in many cases difficult.

The case of gratings is more simple and important than the others, and therefore shall be considered in detail.

If a series of fine equidistant lines ruled on glass, or a series of fine equidistant wires, be placed before the eye or before a telescope, and a distant point or line of light be viewed through the grating thus formed, we see on each side of the bright point or line a series of equidistant spectra, all having their violet ends directed inwards.

To explain these appearances, let us suppose the telescope removed, and the spectra received on a distant screen.

In figure 465 let O represent the luminous point, AB the grating, and CD the distant screen.

We conceive of the effect on the screen of the light transmitted

Fig. 465.

through the grating in the following manner. The ether in the transparent intervals of the grating becomes simultaneously disturbed and kept in vibration by the light from O. The disturbance of each point in those intervals becomes the origin of a spherical wave, as in art. 576, and the effect produced at any point of the screen is the sum of the effects due to the action of the waves thus proceeding from all the transparent intervals. Now, at the point *o*, which is equidistant from all parts of the grating, all these waves will arrive in the same phase, and will, therefore, reinforce each other, and give a bright point.

At other points, *pp*, on each side of *o*, whose distance from successive intervals of the grating differ by one wave length, or any whole number of wave lengths, the vibrations will also arrive in the same phase, and produce brightness. But at intermediate points the vibrations will arrive from different points of the grating in all phases, and will, therefore, neutralise each other and give rise to darkness.

The fact that the spectra on each side of the central one are coloured

arises from the wave lengths being different for different colours; and the measurement of the distances between the spectra corresponding to different colours affords the most accurate method of determining these wave lengths.

586. **Colours of thin plates. Newton's rings.**—All transparent bodies, solids, liquids, or gases, when in sufficiently fine laminæ, appear

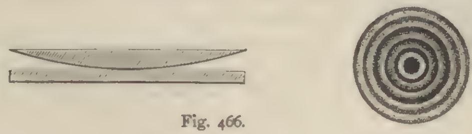


Fig. 466.

coloured with very bright tints, especially by reflection. Crystals which cleave easily, and can be attained in very thin plates, such as mica and selenite, show this phenomenon, which is also well seen in soap bubbles. A drop of oil spread rapidly over a large sheet of water exhibits all the colours of the spectra in a constant order. A soap bubble appears white at first, but in proportion as it is blown out, brilliant iridescent colours appear, especially at the top, where it is thinnest. These colours are arranged in horizontal zones around the summit, which appears black when there is not thickness enough to reflect light, and the bubble then suddenly bursts.

Newton, who first studied the phenomena of the coloured rings in soap bubbles, wishing to investigate the relation between the thickness of the thin plate, the colour of the rings, and their extent, produced them by means of a layer of air interposed between two glasses, one plane and the other convex, and with a very long focus. The two surfaces being cleaned and exposed in ordinary light in front of a window, so as to reflect light, there is seen at the point of contact a black spot surrounded by six or seven coloured rings, the tints of which become gradually less strong. If the glasses are viewed by transmitted light, the centre of the rings is white, and each of the colours is exactly complementary of that of the rings by reflection.

With homogeneous light, red for example, the rings are successively black and red; the diameters of corresponding rings are less as the colour is more refrangible, but with white light the rings are of the different colours of the spectrum, which arises from the fact that, as the rings of the different simple colours have different diameters, they are not exactly superposed, but are more or less separated.

If the focal length of the lens is from three to four yards, the rings can be seen with the naked eye; but if the length is less, the rings must be looked at with a lens.

587. **Explanation of Newton's rings.**—Newton's rings, and all phenomena of thin plates, are simple cases of interference.

In fig. 467, let MNOP represent a thin plate of a transparent body, on which a pencil of parallel rays of homogeneous light, *ab*, impinges; this will be partially reflected in the direction *bc*, and partially refracted

towards *d*. But the refracted ray will undergo a second reflection at the surface, OP; the reflected ray will emerge at *e* in the same direction as the pencil of light reflected at the first surface; and consequently the two pencils *bc* and *ef* will destroy or augment each other's effect according as they are in the same or different phases. We shall thus have an effect produced similar to that of the fringes.

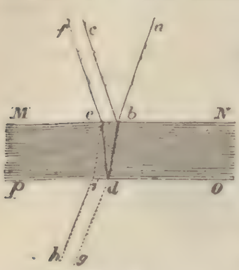


Fig. 467.

It is usual to speak of the successive rings as the first, second, third, etc. By the *first* ring is understood that of least diameter. Newton determined by calculation the thickness of the layer of air at the points where the successive rings were formed, and found that the thicknesses corresponding to the successive *dark* rings are proportional to the numbers 0, 2, 4, 6 . . . . . , while for the *bright* rings the thicknesses were proportional to 1, 3, 5 . . . . . He found that for the first bright ring the thickness was $\frac{1}{175000}$ of an inch, when the light used was the brightest part of the spectrum, that is the part on the confines of the orange and yellow rays. He further found that for rings of the same order the diameter is greater as the refrangibility of the light producing it is less.

POLARISATION OF LIGHT.

588. **Polarisation by double refraction.**—It has been already seen that, when a ray of light passes through a crystal of Iceland spar, it becomes divided into two rays of *equal intensity*, viz. the ordinary ray, and the extraordinary ray. These rays are found to possess other peculiarities, which are expressed by saying they are *polarised*, namely, the ordinary ray in a principal plane, and the extraordinary ray in a plane at right angles to a principal plane. The phenomena which are thus designated may be described as follows :—Suppose a ray of light which has undergone *ordinary* refraction in a crystal of Iceland spar to be allowed to pass through a second crystal, it will generally be divided into two rays, namely, one ordinary, and the other extraordinary, but of *unequal intensities*. If the second crystal be turned round until the two principal planes coincide, that is, until the crystals are in similar or in opposite positions, then the extraordinary ray disappears, and the ordinary ray is at its greatest intensity; if the second crystal is turned further round, the extraordinary ray reappears, and increases in intensity as the angle increases, while the ordinary ray diminishes in intensity until the principal planes are at right angles to each other, when the extraordinary ray is at its greatest intensity, and the ordinary ray vanishes. These are the phenomena produced when the ray which experienced ordinary refraction in the first crystal passes through the second. If the ray which has experienced extraordinary refraction in the first crystal is allowed to pass

through the second crystal, the phenomena are similar to those above described, but when the principal planes coincide, an extraordinary ray alone emerges from the second crystal, and when the planes are at right angles, an ordinary ray alone emerges.

These phenomena may also be thus described :—Let O and E denote the ordinary and extraordinary rays produced by the first crystal. When O enters the second crystal, it generally gives rise to two rays, an ordinary (O*o*), and an extraordinary (O*e*), of unequal intensities. When E enters the second crystal, it likewise gives rise to two rays, viz. an ordinary (E*o*), and an extraordinary (E*e*), of unequal intensities ; the intensities varying with the angle between the principal planes of the crystals. When the principal planes coincide, only two rays, viz. O*o* and E*e*, emerge from the second crystal, and when the planes are at right angles, only two rays, viz. O*e* and E*o*, emerge from the second crystal. Since O gives rise to an ordinary ray when the principal planes are parallel, and E gives rise to an ordinary ray when they are at right angles, it is manifest that O is related to the principal plane in the same manner that E is related to a plane at right angles to a principal plane.

This phenomenon, which is produced by all double refracting crystals, was observed by Huyghens in Iceland spar, and in consequence of a suggestion of Newton's was afterwards called *polarisation*. It remained, however, an isolated fact until the discovery of polarisation by reflection recalled the attention of physicists to the subject. The latter discovery was made by Malus in 1808.

589. **Polarisation by reflection.**—When a ray of light, *ab* (fig. 468), falls on a polished unsilvered glass surface, *fghi*, inclined to it at an angle of 35° 25′, it is reflected, and the reflected ray is polarised in the plane of reflection. If it were transmitted through a crystal of Iceland spar, it would be transmitted without bifurcation, and undergo an ordinary refraction, when the principal plane coincides with the plane of reflection; it would also be transmitted without bifurcation but undergo extraordinary refraction, when the principal plane is at right angles to the plane of reflection; in other positions of the crystal it would give rise to an ordinary and an extraordinary ray of different intensities, according to the angle between the plane of reflection and the principal plane of the crystal. The peculiar property which the light has acquired by reflection at the surface *fghi* can also be exhibited as follows:—Let the polarised ray *bc* be received at *c*, on a second surface of unsilvered glass, at the same angle, viz. 35° 25′. If the surfaces are parallel, the ray is reflected; but if the second plate is caused to turn round *cb*, the intensity of the

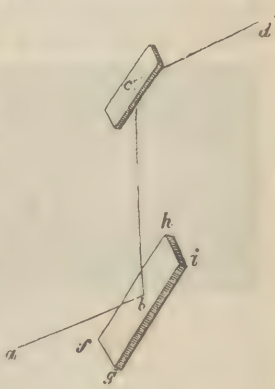


Fig. 468.

reflected ray continually diminishes, and when the glass surfaces are at right angles to each other, no light is reflected. By continuing to turn the upper mirror, the intensity of the reflected ray gradually increases, and attains a maximum value when the surfaces are again parallel.

The above statement will serve to describe the phenomenon of polarisation by reflection so far as the principles are concerned ; the apparatus best adapted for exhibiting the phenomenon will be described further on.

590. **Angle of polarisation.**—The polarising angle of a substance is the angle which the incident ray must make with the normal to a plane polished surface of that substance in order that the polarisation be complete. For glass this angle is 54° 35′, and if in the preceding experiment the lower mirror were inclined at any other angle than this, the light would not be completely polarised in any position ; this would be shown by its being partially reflected from the upper surface in all positions. Such light is said to be *partially polarised.* The polarising angle for water is 52° 45′ ; for quartz, 57° 32′ ; for diamond, 68° ; and it is 56° 30′ for obsidian, a kind of volcanic glass which is often used in these experiments.

Light which is reflected from the surface of water, from a slate roof, from a polished table, is all more or less polarised. The ordinary light of the atmosphere is frequently polarised, especially in the earlier and later periods of the day, when the solar rays fall obliquely on the atmosphere. Almost all reflecting surfaces may be used as polarising mirrors. Metallic surfaces form, however, an important exception.

Brewster has discovered the following remarkably simple law in reference to the polarising angle :—

The polarising angle of a substance is that angle of incidence for which the reflected polarised ray is at right angles to the refracted ray.

Thus, in fig. 469, if *si* is the incident, *ir* the refracted, and *if* the reflected ray, the polarisation is most complete when *fi* is at right angles to *ir*.

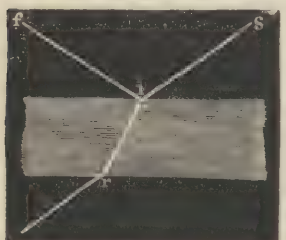


Fig. 469.

The *plane of polarisation* is the plane of reflection in which the light becomes polarised ; it coincides with the plane of incidence, and, therefore, contains the polarising angle.

591. **Polarisation by single refraction.**—When an unpolarised luminous ray falls upon a glass plate placed at the polarising angle, one part is reflected ; the other part, in passing through the glass, becomes refracted, and the transmitted light is now found to be partially polarised. If the light which has passed through one plate, and whose polarisation is very feeble, be transmitted through a second plate parallel to the first, the effects become more marked, and by ten or twelve plates are tolerably complete. A bundle of such plates, for which the best material is the glass used for covering microscopic objects, fitted in a tube at the polarising angle, is frequently used for examining or producing polarised light.

If a ray of light fall at any angle on a transparent medium, the same holds good with a slight modification. In fact, part of the light is reflected and part refracted, and both are found to be partially polarised, *equal quantities in each being polarised, and their planes of polarisation being at right angles to each other.* It is, of course, to be understood that the polarised portion of the reflected light is polarised in the plane of reflection, which is likewise the plane of refraction.

592. **Polarising instruments.**—Every instrument for investigating the properties of polarised light consists essentially of two parts, one for polarising the light, the other for ascertaining or exhibiting the fact of light having undergone polarisation. The former part is called the polariser, the latter the analyser. Thus in art. 588 the crystal producing the first refraction is the *polariser*, that producing the second refraction is the *analyser*. In art. 589, the mirror at which the first reflection takes place

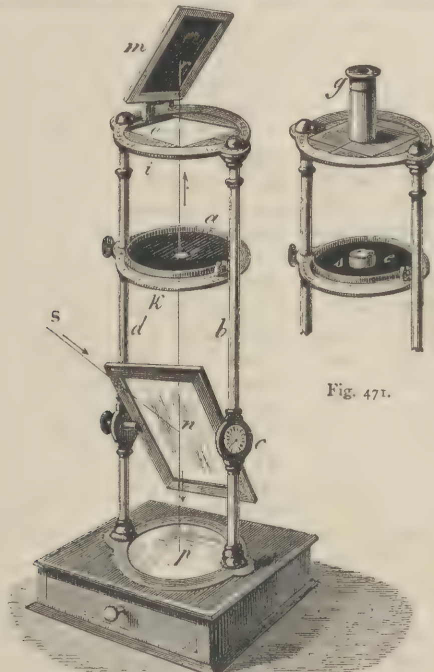


Fig. 471.

Fig. 470.

is the polariser, that at which the second reflection takes place is the analyser. Some of the most convenient means of producing polarised light will now be described, and it will be remarked that any instrument that can be used as a polariser can also be used as an analyser. The experimenter has therefore considerable liberty of selection.

593. **Norremberg's apparatus.**—The most simple but complete instrument for polarising light is that invented by M. Norremberg. It may be used for repeating most of the experiments on polarised light.

It consists of two brass rods *b* and *d* (fig. 470), which support an unsilvered mirror, *n*, of ordinary glass, moveable about a horizontal axis. A small graduated circle indicates the angle of inclination of the mirror. Between the feet of the two columns there is a silvered glass, *p*, which is fixed and horizontal. At the upper end of the columns there is a graduated plate, *i*, in which a circular disc, *o*, rotates. This disc, in which there is a square aperture, supports a mirror of black glass, *m*, which is inclined to the vertical at the polarising angle. An annular disc, *k*, can be fixed at different heights on the columns by means of a screw. A second ring, *a*, may be moved around the axis. It supports a black screen, in the centre of which there is a circular aperture.

When the mirror *n* makes with the vertical an angle of 35° 25′, which is the complement of the polarising angle for glass, the luminous rays, S*n*, which meet the mirror at this angle, become polarised, and are reflected in the direction *np* towards the mirror *p*, which sends them in the direction *pnr*. After having passed through the glass, *n*, the polarised ray falls upon the blackened glass *m* under an angle of 35° 25′, because the mirror makes exactly the same angle with the vertical. But if the disc, *o*, to which the mirror, *m*, is fixed, be turned horizontally, the intensity of the light reflected from the upper mirror gradually diminishes, and totally disappears when it has been moved through 90°. This position is that represented in the diagram : the plane of incidence on the upper mirror is then perpendicular to the plane of incidence, S*np*, on the mirror *n*. When the upper mirror is again turned, the intensity of the light increases until it has passed through 180°, when it again reaches a maximum. The mirrors *m* and *n* are then parallel. The same phenomena are repeated as the mirror *m* continues to be turned in the same direction, until it again comes into its original position. The intensity of the reflected light being greatest when the mirrors are parallel, and being reduced to zero when they are at right angles. If the mirror *m* is at a greater or less angle than 35° 25′, a certain quantity of light is reflected in all positions of the plane of incidence.

594. **Tourmaline.**—The primary form of this crystal is a regular hexagonal prism. Tourmaline, as already stated, is a negative uniaxial crystal, and its optic axis coincides with the axis of the prism. For optical purposes a plate is cut from it parallel to the axis. When a ray of light passes through such a plate, an ordinary ray and an extraordinary ray are produced, polarised in planes at right angles to each other, viz. the former in a plane at right angles to the plate parallel to the axis, and the latter in a plane at right angles to the axis. The crystal possesses, however, the remarkable property of rapidly absorbing the ordinary ray ; consequently, when a plate of certain thickness is used, the extraordinary ray alone emerges, in other words, a beam of common light emerges from the plate of tourmaline polarised in a plane at right angles to the axis of the crystal. If the light thus transmitted be viewed through another similar

plate held in a parallel position, little change will be observed, excepting that the intensity of the transmitted light will be about equal to that which passes through a plate of double the thickness; but if the second tourmaline be slowly turned, the light will become feebler, and will ultimately disappear when the axes of the two plates are at right angles.

The objections to the use of the tourmaline are that it is not very transparent, and that plates of considerable thickness must be used if the polarisation is to be complete. For unless the ordinary ray is completely absorbed, the emergent light will be only partially polarised.

Mr. Herepath has lately discovered that sulphate of iodoquinine has the property of polarising light in a remarkable degree. Unfortunately, it is very fragile and difficult to obtain in large crystals.

595. **Double refracting prisms of Iceland spar.**—When a ray of light passes through an ordinary rhombohedron of Iceland spar, the ordinary and extraordinary rays emerge parallel to the original ray, consequently the separation of the rays is proportional to the thickness of the prism. But if the crystal is cut so that its faces are inclined to each other, the deviations of the ordinary and extraordinary rays will be different, they will not emerge parallel, and their separation will be greater as their distance from the prism increases. The light, however, in passing through the prism becomes decomposed, and the rays will be coloured. It is therefore necessary to achromatise the prism, which is done by combining it with a prism of glass with its refracting angle turned in the contrary direction (fig. 472). In order to obtain the greatest amount of divergence, the refracting edges of the prism should be cut parallel to the optic axis, and this is always done.

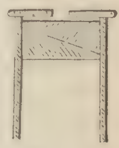


Fig. 472.

Let us suppose that a ray of polarised light passes along the axis of the cylinder (fig. 472), and let us suppose that the cylinder is caused to turn slowly round its axis; then the resulting phenomena are exactly like those already described (586). Generally there will be an ordinary and extraordinary ray produced, whose relative intensities will vary as the tube is turned. But in two opposite positions the ordinary ray alone will emerge, and in two others at right angles to the former the extraordinary ray will alone emerge. When the ordinary ray alone emerges, the principal plane of the crystal, that is, a plane at right angles to its face, and parallel to its refracting edge, coincides with the original plane of polarisation of the ray. Consequently, by means of the prism, it can be ascertained both that the ray is polarised, and likewise the plane in which it is polarised.

596. **Nicol's prism.**—The Nicol's prism is one of the most valuable means of polarising light, for it is perfectly colourless, it polarises light completely, and it transmits only one beam of polarised light, the other being entirely suppressed.

It is constructed out of a rhombohedron of Iceland spar, about an inch in height and ⅓ of an inch in breadth. This is bisected in the plane which passes through the obtuse angles, as shown in fig. 474, that is

along the plane *abcd* (fig. 462). The two halves are then again joined in the same order by means of Canada balsam.

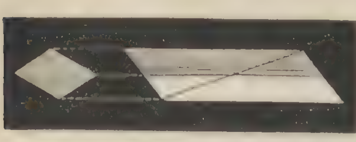


Fig. 473.

Fig. 474.

The principle of the Nicol's prism is this: the refractive index of Canada balsam 1·549 is less than the ordinary index of Iceland spar 1·654, but greater than its extraordinary index 1·483. Hence, when a luminous ray, SC, fig. 474, enters the prism, the ordinary ray undergoes total reflection on the surface *ab*, and takes the direction C*d*O, by which it is refracted out of the crystal; while the extraordinary ray, C*e*, emerges alone. Since the Nicol's prism allows only the extraordinary ray to pass, it may be used, like a tourmaline, as an analyser or as a polariser.

597. **Physical theory of polarised light.**—The explanation of the dark bands produced by the interference of light is stated in art. 582 to resemble exactly that of the formation of nodes and loops given in art. 246.

It might hence be supposed that the vibrations producing light are similar to those producing sound. But this is by no means the case. In fact, if art. 588 be examined, it will be found that no assumption is there made as to the *direction* in which the vibrating particles move, and accordingly that explanation is equally true whether the particles vibrate in the direction AB, BA, or at right angles to AB. As a matter of fact, the former is the case with the vibrations producing sound, the latter with the vibrations producing light. In other words, the vibrations producing sound take place in the direction of propagation, the vibrations producing light are *transversal* to the direction of propagation.

This assumption as to the direction of the vibration of the particles of ether producing light is rendered necessary, and is justified by the phenomena of polarisation.

When a ray of light is polarised, all the particles of ether in that ray vibrate in straight lines parallel to a certain direction in the front of the wave corresponding to the ray.

When a ray of light enters a double refracting medium, such as Iceland spar, it becomes divided into two, as we have already seen. Now it can be shown to be in strict accordance with mechanical principles that, if a medium possesses unequal elasticity in different directions, a plane wave produced by transversal vibrations entering that medium will give rise to two plane waves moving with different velocities within the medium, and the vibrations of the particles in front of these waves will be in directions parallel respectively to two lines at right angles to each other. If, as is assumed in the undulatory theory of light, the ether exists

in a double refracting crystal in such a state of unequal elasticity, then the two plane waves will be formed as above described, and these having different velocities will give rise to two rays of unequal refrangibility (compare art. 576). This is the physical account of the phenomenon of double refraction. It will be remarked that the vibrations corresponding to the two rays are transversal, rectilinear, and in directions perpendicular to each other in the rays respectively. Accordingly, the same theory accounts for the fact that the two rays are both polarised, and in planes at right angles to each other.

It is a point still unsettled whether, when a ray of light is polarised with respect to a given plane, the vibrations take place in directions within or perpendicular to that plane. Fresnel was of the latter opinion. It is, however, convenient in some cases to regard the plane of polarisation as that in which the vibrations take place.

COLOURS PRODUCED BY THE INTERFERENCE OF POLARISED LIGHT.

598. **Laws of the interference of polarised rays.**—After the discovery of polarisation, Fresnel and Arago tried whether polarised rays presented the same phenomena of interference as ordinary rays. They were thus led to the discovery of the following laws in reference to the interference of polarised light, and, at the same time, of the brilliant phenomena of coloration, which will be presently described :—

I. When two rays polarised in the same plane interfere with each other, they will produce by their interference fringes of the very same kind as if they were common light.

II. When two rays of light are polarised at right angles to each other, they produce no coloured fringes in the same circumstances under which two rays of common light would produce them. When the rays are polarised in planes inclined to each other at any other angles, they produce fringes of intermediate brightness, and if the angle is made to change, the fringes gradually decrease in brightness from 0° to 90°, and are totally obliterated at the latter angle.

III. Two rays originally polarised in planes at right angles to each other may be subsequently brought into the same plane of polarisation without acquiring the power of forming fringes by their interference.

IV. Two rays polarised at right angles to each other, and afterwards brought into the same plane of polarisation, produce fringes by their interference like rays of common light, provided they originated in a pencil the whole of which was originally polarised in any one plane.

V. In the phenomena of interference produced by rays that have suffered double refraction, a difference of half an undulation must be allowed, as one of the pencils is retarded by that quantity from some unknown cause.

599. **Effect produced by causing a pencil of polarised rays to traverse a double refracting crystal.**—The following important experiment may be made most conveniently by Norremberg's apparatus

(fig. 470). At *g* (fig. 471), there is a Nicol's prism. A plate of a double refracting crystal cut parallel to its axis is placed on the disc at *e*. In the first place, however, suppose the plate of the crystal to be removed. Then, since the Nicol's prism allows only the extraordinary ray to pass, when it is turned so that its principal plane coincides with the plane of reflection, no light will be transmitted (596). Place the plate of doubly refracting crystal, which is supposed to be of moderate thickness, in the path of the reflected ray at *e*. Light is now transmitted through the Nicol's prism. On turning the plate, the intensity of the transmitted light varies ; it reaches its maximum when the principal plane of the plate is inclined at an angle of 45° to the plane of reflection, and disappears when these planes either coincide with or are at right angles to each other. The light in this case is white. The interposed plate may be called the *depolarising plate*. The same or equivalent phenomena are produced when any other analyser is used. Thus, suppose the double refracting prism to be used. Suppose the depolarising plate to be removed. Then, generally, two rays are transmitted, but if the principal plane of the analyser is turned into the plane of primitive polarisation, the ordinary ray only is transmitted, and then, when turned through 90°, the extraordinary ray only is transmitted. Let the analyser be turned into the former position, then, when the depolarising plate is interposed, both ordinary and extraordinary rays are seen, and when the depolarising plate is slowly turned round, the ordinary and extraordinary rays are seen to vary in intensity, the latter vanishing when the principal plane of the polarising plate either coincides with or is at right angles to the plane of primitive polarisation.

600. **Effect produced when the plate of crystal is very thin.**—In order to exhibit this, take a thin film of *selenite* or *mica* between the twentieth and sixtieth of an inch thick, and interpose it as in the last article. If the thickness of the film is uniform, the light now transmitted through the analyser will be no longer white, but of a uniform tint ; the colour of the tint being different for different thicknesses, for instance, red, or green, or blue, or yellow, according to the thickness ; the intensity of the colour depending on the inclination of the principal plane of the film to the plane of reflection, being greatest when the angle of inclination is 45°. Let us now suppose the crystalline film to be fixed in that position in which the light is brightest, and suppose its colour to be *red*. Let the analyser (the Nicol's prism) be turned round, the colour will grow fainter, and when it has been turned through 45°, the colour disappears, and, no light is transmitted ; on turning it farther, the complementary colour, *green*, makes its appearance, and increases in intensity until the analyser has been turned through 90°; after which the intensity diminishes until an angle of 135° is attained, when the light again vanishes, and, on increasing the angle, it changes again into red. Whatever be the colour proper to the plate, the same series of phenomena will be observed, the colour passing into its complementary when the analyser is turned. That the colours are really complementary is proved by using a double refracting prism as analyser. In this case two rays are transmitted, each

of which goes through the same changes of colour and intensity as the single ray described above, but whatever be the colour and intensity of the one ray in a given position, the other ray will have the same when the analyser has been turned through an angle of 90°. Consequently, these two rays give simultaneously the appearances which are successively presented in the above case by the same ray at an interval of 90°. If now the two rays are allowed to overlap they produce white light ; thereby proving their colours to be complementary.

Instead of using plates of different thickness to produce different tints, the same plate may be employed inclined at different angles to the polarised ray. This causes the ray to traverse the film obliquely, and, in fact, amounts to an alteration in its thickness.

With the same substance, but with plates of increasing thickness, the tints follow the laws of the colours of Newton's rings (586). The thickness of the depolarising plate must, however, be different from that of the layer of air in the case of Newton's rings to produce corresponding colours. Thus corresponding colours are produced by a plate of mica and a layer of air when the thickness of the former is about 400 times that of the latter. In the case of selenite the thickness is about 230 times ; and, in the case of Iceland spar, about 13 times that of the corresponding layer of air.

601. **Theory of the phenomena of depolarisation.**—The phenomena described in the last articles admit of complete explanation by the undulatory theory, but not without the aid of abstruse mathematical calculations. What follows will show the nature of the explanation. Let us suppose, for convenience, that in the case of a polarised ray the particles of ether vibrate in the plane of polarisation (see art. 597), and that the analyser is a double refracting prism, with its principal plane in the plane of primitive polarisation ; then the vibrations being wholly in that plane have no resolved part in a plane at right angles to it, and, consequently, no extraordinary ray passes through the analyser ; in other words, only an ordinary ray passes. Now take the depolarising plate cut parallel to the axis, and let it be interposed in such a manner that its principal plane makes any angle (θ) with the plane of primitive polarisation. The effect of this will be to cause the vibrations of the primitive ray to be resolved in the principal plane, and at right angles to the principal plane, thereby giving rise to an ordinary ray (O), and an extraordinary ray (E), which, however, do not become separated on account of the thinness of the depolarising plate. They will not form a single plane polarised ray on leaving the plate, since they are unequally retarded in passing through it, and consequently leave it in different phases. Since neither of the planes of polarisation of O and E coincides with the principal plane of the analyser, the vibrations composing them will again be resolved by the analyser into vibrations in and at right angles to the principal plane, viz. O gives rise to O*o* and O*e*, and E gives rise to E*o* and E*e*. But the vibrations composing O*o* and E*o* being in the same plane give rise to a single ordinary ray, I*o*, and in like manner O*e* and E*e* give rise to a single

extraordinary ray, I*e*. Thus the interposition of the depolarising plate restores the extraordinary ray.

Suppose the angle θ to be either 0° or 90°. In either case the vibrations are transmitted through the depolarising plate without resolution, consequently they remain wholly in the plane of primitive polarisation, and on entering the analyser cannot give rise to an extraordinary ray.

If the Nicol's prism is used as an analyser, the ordinary ray is suppressed by mechanical means. Consequently only I*e* will pass through the prism, and that for all values of θ except 0° and 90°.

A little consideration will show that the joint intensities of all the rays existing at any stage of the above transformations must continue constant, but that the intensities of the individual rays will depend on the magnitude of θ, and when this circumstance is examined in detail, it explains the fact that I*e* increases in intensity as θ increases from 0° to 45°, and then decreases in intensity as θ increases from 45° to 90°.

In regard to the colour of the rays, it is to be observed that the formulæ for the intensities of I*o* and I*e* contain a term depending on the length of the wave and the thickness of the plate. Consequently, when white light is used, the relative intensities of its component colours are changed, and, therefore, I*o* and I*e* will each have a prevailing tint, which will be different for different thicknesses of the plate. The tints will, however, be complementary, since, the joint intensities of I*o* and I*e* being the same as that of the original ray, they will, when superimposed, restore all the components of that ray in their original intensities, and therefore produce white light.

602. **Coloured rings produced by polarised light in traversing double refracting films.**—In the experiments with Norremberg's apparatus, which have just been described (592), a pencil of parallel rays

Fig. 475.

traverses the film of crystal perpendicularly to its faces, and as all parts of the film act in the same manner, there is everywhere the same tint. But when the incident rays traverse the plate under different obliquities, which comes to the same thing as if they traversed plates differing in thickness, coloured rings are formed similar to Newton's rings.

The best method of observing these new phenomena is by means of the *tourmaline pincette*. This is a small instrument consisting of two tourmalines, cut parallel to the axis, each of them being fitted in a copper disc. These two discs, which are perforated in the centre, and blackened, are mounted in two rings of silvered copper, which is coiled, as shown in the figure, so as to form a spring, and press together the tourmalines. The tourmalines turn with the disc, and may be so arranged that their axes are either perpendicular or parallel.

The crystal to be experimented upon being fixed in the centre of a cork

disc is placed between the two tourmalines, and the pincette is held before the eye so as to view diffused light. The tourmaline farthest from the eye acts as polariser, and the other as analyser. If the crystal thus viewed is uniaxial, and cut perpendicularly to the axis, and a homogeneous light, red for instance, is looked at, a series of alternately dark and red rings are seen. With another simple colour, similar rings are obtained, but their diameter decreases with the refrangibility of the colour. On the other hand, the diameters of the rings diminish when the thickness of the plates increases, and beyond a certain thickness no more rings are produced. If, instead of illuminating the rings by homogeneous light, white light be used, as the rings of the different colours produced have not the same diameter, they are partially superposed, and produce very brilliant variegated colours.

The position of the crystal has no influence on the rings, but this is not the case with the relative position of the two tourmalines. For instance, in experimenting on Iceland spar cut perpendicular to the axis, and from 1 to 20 millimeters in thickness, when the axes of the tourmalines are perpendicular, a beautiful series of rings is seen brilliantly coloured, and traversed by a black cross, as shown in fig. 476. If the axes of the tour-

Fig. 476.

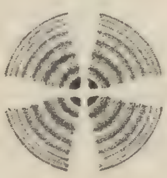


Fig. 477.

Fig. 478.

malines are parallel, the rings have tints complementary to those they had at first, and there is a white cross (fig. 477), instead of a black one.

In order to understand the formation of these rings when polarised light traverses double refracting films, it must first be premised that these films are traversed by a converging conical pencil, whose summit is the eye of the observer. Hence it follows that the virtual thickness of the film which the rays traverse increases with their divergence; but for rays of the same obliquity this thickness is the same: hence there result different degrees of retardation of the ordinary with respect to the extraordinary ray at different points of the plate, and consequently different colours are produced at different distances from the axis, but the same colours will be produced at the same distance from the axis, and consequently the colours are arranged in circles round the axis. The arms of the black cross are parallel to the optic axis of each of the tourmalines, and are due to an absorption of the polarised light in these directions. When the tourmalines are parallel the vibrations are transmitted, and hence the white cross.

Analogous effects are produced with all uniaxial crystals; for instance, tourmaline, emerald, sapphire, beryl, mica, pyromorphite, and ferrocyanide of potassium.

603. **Rings in biaxial crystals.**—In biaxial crystals, coloured rings are also produced, but their form is more complicated. The coloured bands, instead of being circular and concentric, have the form of curves, with two centres, the centre of each system corresponding to an axis of the crystal. Figs. 479, 480, and 481 represent the curves seen when a plate of nitre, cut perpendicularly to the axis, is placed between the two

Fig. 479. Fig. 480. Fig. 481.

tourmalines, the plane containing the axis of the nitre being in the plane of primitive polarisation. When the axes of the two tourmalines are at right angles to each other the fig. 479 is obtained. On turning the crystal without altering the tourmalines, the fig. 480 is seen, which changes into fig. 481 when the crystal has been turned 45°. If the axes of the tourmalines are parallel, the same coloured curves are obtained, but the colours are complementary, and the black cross changes into white. The angle of the optic axis in the case of nitre is only 5° 20′, and hence the whole system can be seen at once. But when the angle exceeds 20° to 25°, the two systems of curves cannot be simultaneously seen. There is then only one dark bar instead of the cross, and the bands are not oval but circular. Fig. 478 represents the phenomenon as seen with arragonite.

Herschel, who has carefully measured the rings produced by biaxial crystals, refers them to the kind of curve known in geometry as the *lemniscate*, in strict accordance with the results of the undulatory theory of light.

The observation of the system of rings which plate of crystals give in polarised light presents a means of distinguishing between optical uniaxial and optical biaxial crystals, even in cases in which no conclusion can be drawn as to the system in which a mineral crystallises from mere morphological reasons. In this way, the optical investigation becomes a valuable aid in mineralogy, as, for example, in the case of mica, of which there are two mineralogical species, the uniaxial and the biaxial.

All the phenomena which have been described are only obtained by means of polarised light. Hence a double refracting film, with either a

Nicol's prism or a tourmaline as analyser, may be used to distinguish between polarised and unpolarised light, that is, as a polariscope.

604. **Colours produced by compressed or by unannealed glass.**—Ordinary glass is not endowed with the power of double refraction. It

Fig. 482.

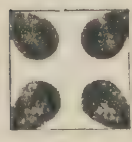


Fig. 483.

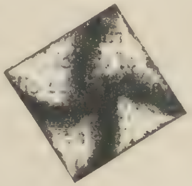


Fig. 484.

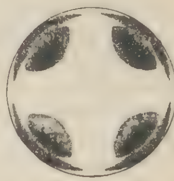


Fig. 485.

Fig. 486.

Fig. 487.

acquires this property, however, if by any cause its elasticity becomes more modified in one direction than in another. In order to effect this, it may be strongly compressed in a given direction, or it may be curved, or tempered, that is to say, cooled after having been heated. If the glass is then traversed by a beam of polarised light, effects of colour are obtained which are entirely analogous to those described in the case of doubly refracting crystals. They are, however, susceptible of far greater variety, according as the plates of glass have a circular, square, rectangular, or triangular shape, and according to the degree of tension of their particles.

When the polariser is a mirror of black glass, on which the light of the sky is incident, and the analyser is a Nicol's prism, through which the glass plates traversed by polarised light are viewed, figs. 482, 483, 485 represent the appearances presented successively, when a square plate of compressed glass is turned in its own plane; figs. 484 and 487 represent the appearances produced by a circular plate under the same circumstances; and fig. 486, that produced when one rectangular plate is superposed on another. This figure also varies when the system of plates is turned.

Compressed and curved glasses present phenomena of the same kind, which also vary under the same conditions.

ELLIPTICAL, CIRCULAR, AND ROTATORY POLARISATION.

605. **Definition of elliptical and circular polarisation.**—In the cases hitherto considered the particles of ether composing a polarised ray vibrate in parallel straight lines; to distinguish this case from those we are now to consider such light is frequently called *plain polarised light.* It sometimes happens that the particles of ether describe *ellipses* round their positions of rest, the planes of the ellipses being perpendicular to the direction of the ray. If the axes of these ellipses are equal and parallel, the ray is said to be *elliptically polarised.* In this case the particles which, when at rest, occupied a straight line, are, when in motion, arranged in a helix round the line of their original position as an axis, the helix changing from instant to instant. If the axes of the ellipses are equal, they become circles, and the light is said to be *circularly polarised.* If the minor axes become zero, the ellipses coincide with their major axes, and the light becomes *plane polarised.* Consequently, *plane* polarised light and *circularly* polarised light are particular cases of elliptically polarised light.

606. **Theory of the origin of elliptical and circular polarisation.**—Let us in the first place consider a simple pendulum (51) vibrating in any plane, the arc of vibration being small. Suppose that, when in its lowest position, it received a blow in a direction at right angles to the direction of its motion, such as would make it vibrate in an arc at right angles to its arc of primitive vibration, it follows from the law of the composition of velocities (48) that the joint effect will be to make it vibrate in an arc inclined at a certain angle to the arc of primitive vibration, the magnitude of the angle depending on the magnitude of the blow. If the blow communicated a velocity equal to that with which the body is already moving, the angle would be 45°. Next suppose the blow to communicate an equal velocity, but to be struck when the body is at its highest point, this will cause the particle to describe a circle, and to move as a conical pendulum (53). If the blow is struck under any other circumstances, the particle will describe an ellipse. Now as the two blows would produce separately two simple vibrations in directions at right angles to each other, we may state the result arrived at as follows:—If two rectilinear vibrations are superinduced on the same particle in directions at right angles to each other, then: 1. If they are in the same or opposite phases, they make the point describe a rectilinear vibration in a direction inclined at a certain angle to either of the original vibrations. 2. But if their phases differ by 90° or a quarter of a vibration, the particle will describe a circle, provided the vibrations are equal. 3. Under other circumstances the particle will describe an ellipse.

To apply this to the case of polarised light. Suppose two rays of light polarised in perpendicular planes to coincide, each would separately cause the same particles to vibrate in perpendicular directions. Consequently—1. If the vibrations are in the same or opposite phases, the

light resulting from the two rays is plane polarised. 2. If the rays are of equal intensity, and their phases differ by 90°, the resulting light is circularly polarised. 3. Under other circumstances the light is elliptically polarised.

As an example, if reference is made to arts. 599 and 600, it will be seen that the rays denoted by O and E are superimposed in the manner above described. Consequently, the light which leaves the depolarising plate is elliptically polarised. If, however, the principal plane of the depolarising plate is turned so as to make an angle of 45° with the plane of primitive polarisation, O and E have equal intensities, and if further the plate is made of a certain thickness, so that the phases of O and E may differ by 90°, or by a quarter of a vibration, the light which emerges from the plate is circularly polarised. This method may be employed to produce circularly polarised light.

Circular or elliptical polarisation may by either *right-handed* or *left-handed*, or what is sometimes called *dextrogyrate* and *lævogyrate*. If the observer looks along the ray in the direction of propagation, from polariser to analyser, then, if the particles move in the same direction as the hands of a watch, with its face to the observer, the polarisation is right-handed.

607. **Fresnel's rhomb.** — This is a means of obtaining circularly polarised light. We have already seen (606) that, to obtain a ray of circularly polarised light, it is sufficient to decompose a ray of plane polarised light in such a manner as to produce two rays of light of equal intensity polarised in planes at right angles to each other, and differing in their paths by a quarter of an undulation. Fresnel effected this by means of a rhomb, which has received his name. It is made of glass; its acute angle is 54°, and its obtuse 126°. If a ray, *a*, fig. 488, of plane polarised light fall perpendicularly on the face AB, it will undergo two total internal reflections at an angle of about 54°, one at E, and the other at F, and will emerge perpendicularly.

If the plane ABDC be inclined at an angle of 45° to the plane of polarisation, the polarised ray will be divided into two coincident rays with their planes of polarisation at right angles to each other, and it appears that one of them loses exactly a quarter of an undulation, so that on emerging from the rhomb the ray is circularly polarised. If the ray emerging as above from Fresnel's rhomb is examined, it will be found to differ from plane polarised light in this, that, when it passes through a double refracting prism, the ordinary and extraordinary rays are of equal intensity in all positions of the prism. Moreover, it differs from ordinary light in this, that if it passed through a second rhomb placed parallel to the first, there will a second quarter of an undulation lost, so that the parts of the original plane polarised ray will differ by half an undulation, and the

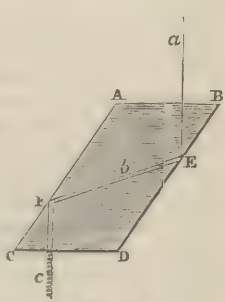


Fig. 488.

emergent ray will be plane polarised; moreover, the plane of polarisation will be inclined at an angle of 45° to ABCD, but on the *other side* from the plane of primitive polarisation.

608. **Elliptical polarisation.**—Our limits will not allow us to enter into this subject, but we may state that, in addition to the method already mentioned (607), elliptically polarised light is generally obtained whenever plane polarised light suffers reflection. Polarised light reflected from metals becomes elliptically polarised, the degree of ellipticity depending on the direction of the incident ray, and of its plane of polarisation, as well as on the reflecting substance. When reflected from silver, the polarisation is almost circular, and from galena almost plane. If elliptically polarised light be analysed by the Nicol's prism, it never vanishes, though at alternate postions it becomes fainter; it is thus distinguished from plane and from circular polarised light. If analysed by Iceland spar neither image disappears, but they undergo changes in intensity.

Light can also be polarised elliptically in Fresnel's rhomb. If the angle between the planes of primitive polarisation and of incidence be any other than 45°, the emergent ray is elliptically polarised.

609. **Rotatory polarisation.**—Rock crystal or quartz possesses a remarkable property which was long regarded as peculiar to itself among all crystals, though it has been since found to be shared by tartaric acid and its salts, together with some other crystalline bodies. This property is called rotatory polarisation, and may be described as follows:—Let a ray of homogeneous light (for example, red light) be polarised, and let the analyser, say a Nicol's prism, be turned till the light does not pass through it. Take a thin section of a quartz crystal cut at right angles to its axis, and place it between the polariser and the analyser with its plane at right angles to the rays. The light will now pass through the analyser. The phenomenon is not the same as that previously described (599), for, if the rock crystal is turned round its axis, no effect is produced, and if the analyser is turned, the ray is found to be *plane polarised*, in a plane inclined at a certain angle to the plane of primitive polarisation. If the light is red, and the plate 1 millimeter thick, this angle is about 17°. In some specimens of quartz the plane of polarisation is turned to the right hand, in others to the left hand. Specimens of the former kind are said to be right-handed, those of the latter kind left-handed. This difference corresponds to a difference in crystallographic structure. The property possessed by rock crystal of turning the plane of polarisation through a certain angle was thoroughly investigated by M. Biot, who, amongst other results, arrived at this:—For a given colour the angle through which the plane of polarisation is turned is proportional to the thickness of the quartz.

610. **Physical explanation of rotatory polarisation.**—The explanation of the phenomenon described in the last article is as follows:—When a ray of polarised light passes along the axis of the quartz crystal, it is divided into two rays of *circularly* polarised light of equal intensity, which pass through the crystal with different velocities. In one the circular polarisation is right-handed, in the other left-handed (606). The existence

of these rays was proved by Fresnel, who succeeded in separating them. On emerging from the crystal, they are compounded into a plane polarised ray, but since they move with unequal velocities within the crystal, they emerge in different phases, and consequently the plane of polarisation will not coincide with the plane of primitive polarisation. This can be readily shown by reasoning similar to that employed in art. 606. The same reasoning will also show that the plane of polarisation will be turned to the right or left, according as the right-handed or left-handed ray moves with the greater velocity. Moreover, the amount of the rotation will depend on the amount of the retardation of the ray whose velocity is least, that is to say, it will depend on the thickness of the plate of quartz. In this manner the phenomena of rotatory polarisation can be completely accounted for.

611. **Coloration produced by rotatory polarisation.**—The rotation is different with different colours; its magnitude depends on the refrangibility, and is greatest with the most refrangible rays. In the case of red light a plate 1 millimeter in thickness will rotate the plane 17°, while a plate of the same thickness will rotate it 44° in the case of violet light. Hence with white light there will, in each position of the analysing Nicol's prism, be a greater or less quantity of each colour transmitted. In the case of a right-handed crystal, when the Nicol's prism is turned to the right, the colours will successively appear from the less refrangible to the more so, that is, in the order of the spectrum from red to violet; with a left-handed crystal in the reverse order. Obviously in turning the Nicol's prism to the left, the reverse of these results will take place.

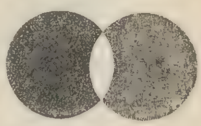


Fig. 489.

When a quartz plate cut perpendicularly to the axis and traversed by a ray of polarised light is looked at through a doubly refracting prism, two brilliantly coloured images are seen, of which the tints are complementary; for their images are partially superposed, and in this position there is a white light (fig. 489). When the prism is turned from left to right, the two images change colours, and assume successively all the colours of the spectrum.

This will be understood from what has been said about the different rotation for different colours. Quartz rotates the plane of polarisation for red 17° for each millimeter, and for violet 44°; hence from the great difference of these two angles, when the polarised light which has traversed the quartz plate emerges, the various simple colours which it contains are polarised in different planes. Consequently, when the rays thus transmitted by the quartz pass through a double refracting prism, they are each decomposed into two others polarised at right angles to each other: the various simple colours are not divided in the same proportion between the ordinary and extraordinary rays furnished by the prism; the two images are, therefore, coloured; but, since these which are wanting in the one occur in the other, the colours of the images are perfectly complementary.

These phenomena of coloration may be well seen by means of Norrem-

berg's apparatus (fig. 470). A quartz plate, *s*, cut at right angles to the axis and fixed in a cork disc, is placed on the screen, *e*; the mirror *n* (fig. 470) being then so inclined that a ray of polarised light passes through the quartz; the latter is viewed through a refracting prism, *g*; when this tube is turned, the complementary images furnished by the passage of polarised light through the quartz are seen.

612. **Rotatory power of liquids.**—Biot has found that a great number of liquids and solutions possess the property of rotatory polarisation. He has further observed that the deviation of the plane of polarisation can reveal differences in the composition of bodies where none is exhibited by chemical analysis. For instance, uncrystallisable grape-sugar deflects the plane of polarisation to the left, while cane-sugar deflects it to the right, although the chemical composition of the two sugars is the same.

The rotatory power of liquids is far less than that of quartz. In concentrated syrup of cane-sugar, which possesses the rotatory power in the highest degree, the power is $\frac{1}{36}$ that of quartz, so that it is necessary to operate upon columns of liquids of considerable length, 8 inches for example.

Fig. 490 represents the apparatus devised by Biot for measuring the

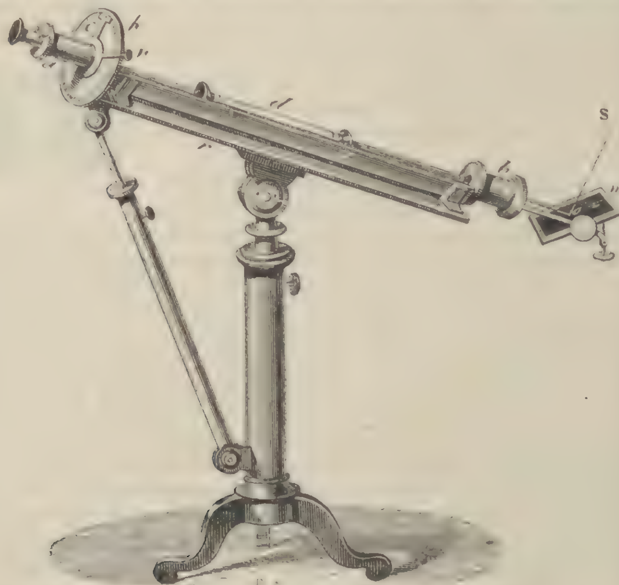


Fig. 490.

rotatory power of liquids. On a copper groove, *g*, fixed to a support, *r*, is a brass tube 20 centimeters long, in which is contained the liquid experimented upon. This tube, which is tinned inside, is closed at each end by

glass plates fastened by screw collars. At *m* is a mirror of black glass, inclined at the polarising angle to the axis of the tubes *bd* and *a*, so that the ray reflected by the mirror *m*, in the direction *bda*, is polarised. In the centre of the graduated circle *h*, inside the tube *a*, and at right angles to the axis *bda*, is a double refracting achromatic prism, which can be turned about the axis of the apparatus by means of a button, *n*. The latter is fixed to a limb, *c*, on which is a vernier, to indicate the number of degrees turned through. Lastly, from the position of the mirror *m*, the plane of polarisation, S*od*, of the reflected ray is vertical, and the zero of the graduation on the circle, *h*, is on this plane.

Before placing the tube *d* in the groove *g*, the extraordinary image furnished by the double refracting prism disappears whenever the limb *c* corresponds to the zero of the graduation, because then the double refracting prism is so turned that its principal section coincides with the plane of polarisation (597). This is the case also when the tube *d* is full of water or any other *inactive* liquid, like alcohol, ether, etc., which shows that the plane of polarisation has not been turned. But if the tube be filled with a solution of cane-sugar or any other *active* liquid, the extraordinary image reappears, and to extinguish it the limb must be turned to a certain extent

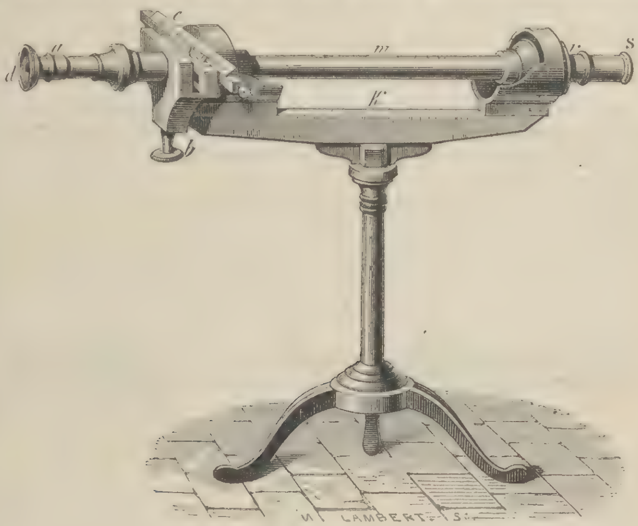


Fig. 491.

either to the right or to the left of zero, according as the liquid is right-handed or left-handed, showing that the polarising plane has been turned by the same angle. With solution of cane-sugar the rotation takes place to the right ; and if with the same solution tubes of different lengths are taken, the rotation is found to increase proportionally to the length, in conformity with art. 609 : further, with the same tube, but with solutions of

various strength, the rotation increases with the quantity of sugar dissolved, so that the quantitative analysis of a solution may be made by means of its angle of deviation.

In this experiment homogeneous light must be used ; for, as the various tints of the spectra have different rotatory powers, white light is decomposed in traversing an active liquid, and the extraordinary image does not disappear completely in any position of the double refracting prism—it simply changes the tint. The transition tint (589) may, however, be observed. To avoid this inconvenience, a piece of red glass is placed in the tube between the eye and the double refracting prism, which only allows red light to pass. The extraordinary image disappears in that case, whenever the principal section of the prism coincides with the plane of polarisation of the red ray.

613. **Soleil's saccharimeter.**—M. Soleil has constructed an apparatus, based upon the rotatory power of liquids, for analysing saccharine substances, to which the name *saccharimeter* is applied.

Figure 491 represents the saccharimeter fixed horizontally on its foot, and fig. 492 gives a longitudinal section, with the modifications which have been introduced by M. Duboscq.

The principle of this instrument is not the amplitude of the rotation of the plane of polarisation, as in Biot's apparatus, but that of *compensation ;* that is to say, a second active substance is used acting in the opposite direction to that analysed, and whose thickness can be altered until the contrary actions of the two substances completely neutralise each other. Instead of measuring the deviation of the plane of polarisation, the thickness is measured which the plate of quartz must have in order to obtain perfect compensation.

The apparatus consists of three parts—a tube containing the liquid to be analysed, a polariser, and an analyser.

The tube *m*, containing the liquid, is made of copper, tinned on the in-

Fig. 492.

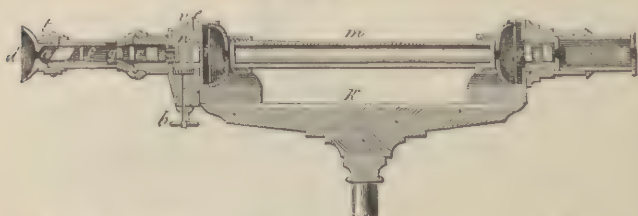


Fig. 493.

Fig. 494.

Fig. 495.

side, and closed at both ends by two glass plates. It rests on a support, *k*, terminated at both ends by tubes *r* and *a*, in which are the crystals

used as analysers and polarisers, and which are represented in section (fig. 492).

In front of the aperture, S (fig. 492), is placed an ordinary moderator lamp. The light emitted by this lamp in the direction of the axis first meets a double refracting prism, *r*, which serves as polariser (594). The ordinary image alone meets the eye, the extraordinary image being projected out of the field of vision in consequence of the amplitude of the angle which the ordinary makes with the extraordinary ray. The double refracting prism is in such a position that the plane of polarisation is vertical, and passes through the axis of the apparatus.

Emerging from the double refracting prism, the polarised ray meets a plate of quartz with double rotation; that is, this plate rotates the plane both to the right and to the left. This is effected by constructing the plate of two quartz plates of opposite rotation placed one on the other, as shown in figure 495, so that the line of separation is vertical and in the same plane as the axis of the apparatus. These plates, cut perpendicularly to the axis, have a thickness of 3·75 millimeters, corresponding to a rotation of 90°, and give a rose-violet tint, called the *tint of passage* or *transition-tint.* As the quartz, whether right-handed or left-handed, turns always to the same extent for the same thickness, it follows that the two quartz, *a* and *b*, turn the plane of polarisation equally, one to the right and the other to the left. Hence, looked at through a double refracting prism, they present exactly the same tint.

Having traversed the quartz, *q*, the polarised ray passes into the liquid in the tube *m*, and then meets a single plate of quartz, *i*, of any thickness, the use of which will be seen presently. The compensator, *n*, which destroys the rotation of the column of liquid *m*, consists of two quartz plates, with the same rotation either to the right or the left, but opposite to that of the plate *i*. These two quartz plates, a section of which is represented in fig. 493, are obtained by cutting obliquely a quartz plate with parallel sides, so as to form two prisms of the same angle, N, N′; superposing, then, these two prisms, as shown in the figure, a single plate is obtained with parallel faces, which can be varied at will. This is effected by fixing each prism to a slide, so as to move it in either direction without disturbing the parallelism. This motion is effected by means of a double rackwork and pinion motion turned by a milled head, *b* (figs. 491, 492).

When these plates move in the direction indicated by the arrows (fig. 493), it is clear that the sum of their thicknesses increases, and that it diminishes when the plates are moved in the contrary direction. A scale and a vernier follow the plates in their motion, and measure the thickness of the compensator. This scale, represented with its vernier in figure 494, has two divisions, with a common zero, one from left to right for right-handed liquids, and another from right to left for left-handed.

When the vernier is at zero of the scale, the sum of the thicknesses of the plates NN′ is exactly equal to that of plate *i*, and as the rotation of the latter is opposed to that of the compensator, the effect is zero. But by moving the plates of the compensator in one or the other direction,

either the compensator or the quartz, i, preponderates, and there is a rotation from left to right.

Behind the compensator is a double refracting prism, c (fig. 492), serving as analyser to observe the polarised ray which has traversed the liquid and the various quartz plates. In order to understand more easily the object of the prism, c, we will neglect for a moment the crystals and the lenses on the left of the drawing. If at first the zero of the vernier, o, coincides with that of the scale, and if the liquid in the tube is inactive, the actions of the compensator, and of the plate i, neutralise each other; and the liquid having no action, the two halves of the plate q, seen through the prism c, give exactly the same tint as has been observed above. But if the tube filled with inactive liquid be replaced by one full of solution of sugar, the rotatory power of this solution is added to that of one of the halves (a or b) of the plate q (viz. that half which tends to turn the plane of polarisation in the same direction as the solution), and subtracted from that of the other. Hence the two halves of the plate q no longer show the same tint; the half a, for instance, is red, while the half b is blue. The prisms of the compensator are then moved, by turning the milled head b, either to the right or to the left, until the difference of action of the compensator and of the plate i compensates the rotatory power of the solution, which takes place when the two halves of the plate Q, with double rotation, revert to their original tint.

The direction of the deviation and the thickness of the compensator are measured by the relative displacement of the scale e, and of the vernier r. Ten of the divisions on the scale correspond to a difference of 1 millimeter in the thickness of the compensator; and as the vernier gives itself tenths of these divisions, it therefore measures differences of $\frac{1}{100}$ in the thickness of the compensator.

When once the tints of the two halves of the plate are exactly the same, and therefore the same as before interposing the solution of sugar, the division on the scale corresponding to the vernier is read off, and the corresponding number gives the strength of the solution. This depends on the principle that 16·471 grains of pure and well-dried sugar-candy being dissolved in water, and the solution diluted to the volume of 100 cubic centimeters, and observed in a tube of 20 centimeters in length, the deviation produced is the same as that effected by a quartz a millimeter thick. In making the analysis of raw sugar, a normal weight of 16·471 grains of sugar is taken, dissolved in water, and the solution made up to 100 cubic centimeters, with which a tube 20 centimeters in length is filled, and the number indicated by the vernier read off, when the primitive tint has been obtained. This number being 42, for example, it is concluded that the amount of crystallisable sugar in the solution is 42 per cent. of that which the solution of sugar-candy contained, and, therefore, 16·471 grains × $\frac{42}{100}$ or 6·918 grains. This result is only valid when the sugar is not mixed with uncrystallisable sugar or some other left-handed substance. In that case the crystallisable sugar, which is right-handed, must be, by means of hydrochloric acid, converted into uncrystallisable sugar, which

is left-handed : and a new determination is made, which, together with the first, gives the quantity of crystallisable sugar.

The arrangement of crystals and lenses, *o*, *g*, *f*, and *a*, placed behind the prism *c*, forms what M. Soleil calls the *producer of sensible tints.* For the most delicate tint, that by which a very feeble difference in the coloration of the two halves of the rotation plate can be distinguished, is not the same for all eyes ; for most people it is of a violet blue tint, like flax-blossom, and it is important either to produce this tint or some other equally sensible to the eye of the observer. This is effected by placing in front of the prism *c*, at first a quartz plate, *o*, cut perpendicular to the axis, then a small Galilean telescope consisting of a double convex glass, *g*, and a double concave glass, *f*, which can be approximated or removed from each other according to the distance of distinct vision of each observer. Lastly, there is a double refracting prism, *c*, acting as polariser in reference to the quartz, and the prism *a* as analyser ; and hence, when the latter is turned either right or left, the light which has traversed the prism *c*, and the plate *o*, changes its tint, and finally gives that which is the most delicate for the experimenter.

614. **Analysis of diabetic urine.**—In the disease *diabetes*, the urine contains a large quantity of fermentescible sugar, called diabetic sugar, which in the natural condition of the urine turns the plane of polarisation to the right. To estimate the quantity of this sugar, the urine is first clarified by heating it with acetate of lead and filtering ; the tube is filled with the clear liquid thus obtained : and the milled head, *b*, turned, until by means of the double rotating plate the same tint is obtained as before the interposition of the urine. Experiment has shown that 100 parts of the saccharimetric scale represent the displacement which the quartz compensators must have when there are 225·6 grains of sugar in a litre ; hence each division of the scale represents 2·256 of sugar. Accordingly, to obtain the quantity of sugar in a given urine, the number indicated by the vernier at the moment at which the primitive tint reappears must be multiplied by 2·256.

615. **Polarisation of heat.**—The rays of heat, like those of light, may become polarised by reflection and by refraction. The experiments on this subject are difficult of execution ; they were first made by Malus and Berard, in 1810 ; after the death of Malus they were continued by the latter philosopher.

In his experiments, the calorific rays reflected from one mirror were received upon a second, just as in Norremberg's apparatus ; from the second they fell upon a small metallic reflector, which concentrated them upon the bulb of a differential thermometer. Berard observed that heat was not reflected when the plane of reflection of the second mirror was at right angles to that of the first. As this phenomenon is the same as that presented by light under the same circumstances, Berard concluded that heat became polarised in being reflected.

The double refraction of heat may be shown by concentrating the sun's rays by means of a heliostat on a prism of Iceland spar, and investigating the resultant pencil by means of a thermopile, which must have a sharp

narrow edge. In this case also there is an ordinary and an extraordinary ray, which follows the same laws as those of light. In the optic axis of the calcspar, heat is not doubly refracted. A Nicol's prism can be used for the polarisation of heat as well as for that of light : a polarised ray does not traverse the second Nicol if the plane of its principal section is perpendicular to the vibrations of the ray. The phenomena of the polarisation of heat may also be studied by means of plates of tourmaline and of mica. The angle of polarisation is virtually the same for heat as for light. In all these experiments the prisms must be very near each other.

The diffraction, and therefore the interference, of rays of heat has recently been established by the experiments of Knoblauch and others. And Forbes, who has repeated Fresnel's experiment with a rhombohedron of rock salt, has found that heat by two total internal reflections is circularly polarised just as is the case with light.

BOOK VIII.

ON MAGNETISM.

CHAPTER I.

PROPERTIES OF MAGNETS.

616. **Natural and artificial magnets.**—*Magnets* are substances which have the property of attracting iron, and the term *magnetism* is applied to the cause of this attraction, and to the resulting phenomena.

This property was known to the ancients; it exists in the highest degree in an ore of iron which is known in chemistry as the magnetic oxide of iron. Its composition is represented by the formula Fe_3O_4. This magnetic oxide of iron, or *lodestone*, as it is called, was first found at Magnesia, in Asia Minor, the name magnet being derived from this circumstance. The name lodestone, which is applied to this natural magnet, was given on account of its being used when suspended as a guiding or leading stone, from the Saxon *lædan*, to lead; so also the word lodestar. Lodestone is very abundant in nature; it is met with in the older geological formations, especially in Sweden and Norway, where it is worked as an iron ore, and furnishes the best quality of iron.

When a bar or needle of steel is rubbed with a magnet, it acquires magnetic properties. Such bars are called *artificial magnets*; they are more powerful than natural magnets, and as they are also more convenient, they will be exclusively referred to in describing the phenomena of magnetism; the best modes of preparing them will be explained in a subsequent article.

617. **Poles and neutral line.**—When a small particle of soft iron is suspended by a thread, and a magnet is approached to it, the iron is attracted towards the magnet, and some force is required for its removal. The force of the attraction varies in different parts of the magnet: it is strongest at the two ends, and is totally wanting in the middle.

This variation may also be seen very clearly when a magnetic bar is placed in iron filings: these become arranged round the ends of the bar in feathery tufts, which decrease towards the middle of the bar, where there are none. That part of the surface of the bar where there is no visible magnetic force is called the *neutral line*; and the points near the ends of the bar where the attraction is greatest are called the *poles*. Every magnet, whether natural or artificial, has two poles and a neutral

line: sometimes, however, in magnetising bars and needles, poles are produced lying between the extreme points. These intermediate points are called *consequent poles.* The shortest line joining the two poles is termed the *axis* of the magnet; in a horseshoe magnet the axis is in the direction of the keeper. The plane at right angles to the axis and passing through the neutral line is called the *equator* of the magnet.

We shall presently see that a freely suspended magnet always sets with one pole pointing towards the north, and the other towards the

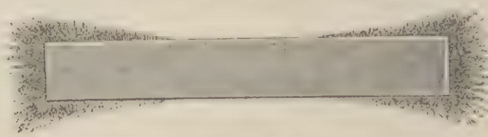


Fig. 496.

south. The end pointing towards the north is called in this country the *north pole*, and the other end is the *south pole.* The end of the magnetic needle pointing to the north is also sometimes called the *marked end* of the needle.

618. **Mutual action of two poles.**—The two poles of a magnet appear identical when they are brought in contact with iron filings, but this identity is only apparent. For when a small magnetic needle, *ab* (fig. 497), is suspended by a fine thread, and the north pole, A, of another needle is brought near its north pole, *a*, a repulsion takes place. If, on the contrary, A is brought near the south pole, *b*, of the moveable needle, the latter is strongly attracted. Hence these two poles, *a* and *b*, are not identical, for one is repelled and the other attracted by the same pole of the magnet, A. It may be shown in the same manner that the two poles of the latter are also different, by successively presenting them to the same pole, *a*, of the moveable needle. In one case there is repulsion, in the other attraction. Hence the following law may be enunciated:

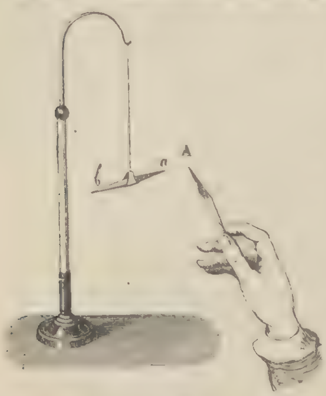


Fig. 497.

Poles of the same name repel, and poles of contrary name attract one another.

The opposite actions of the north and south poles may be shown by the following experiment:—A piece of iron, a key for example, is supported by a magnetised bar. A second magnetised bar of the same dimensions is then moved along the first, so that their poles are contrary (fig. 498). The key remains suspended so long as the two poles are at

some distance, but when they are sufficiently near, the key drops, just as if the bar which supported it had lost its magnetism. This, however, is

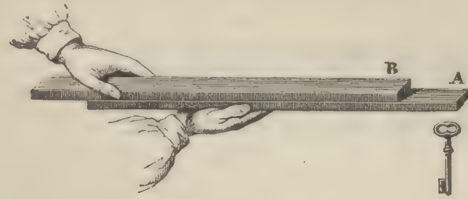


Fig. 498.

not the case, for the key would be again supported if the first magnet were presented to it after the removal of the second bar.

The attraction which a magnet exerts upon iron is reciprocal, which is indeed a general principle of all attractions. It is easily verified by presenting a mass of iron to a moveable magnet, when the latter is attracted.

619. **Hypothesis of two magnetic fluids.**—In order to explain the phenomena of magnetism, the existence of two hypothetical *magnetic fluids* has been assumed, each of which acts repulsively on itself, but attracts the other fluid. The fluid predominating at the north pole of the magnet is called the *north* fluid, and that at the south pole, the *south* fluid. The term 'fluid' is apt to puzzle beginners, from its ambiguity. Ordinarily the idea of a liquid is associated with a fluid ; hence the use of this term to explain the phenomena of magnetism and electricity has produced a widely prevailing impression of the material nature of these two forces. The word fluid, it must be remembered, embraces gases as well as liquids, and here it must be pictured to the mind as representing an invisible, elastic, gaseous atmosphere or shell surrounding the particles of all magnetic substances.

It is assumed that, before magnetisation, these fluids are combined round each molecule, and mutually neutralise each other ; they can be separated by the influence of a force greater than that of their mutual attraction, and can arrange themselves round the molecules to which they are attached, but cannot be removed from them.

The hypothesis of the two fluids is very convenient in explaining magnetic phenomena, and will be adhered to in what follows. But it must not be regarded as anything more than an hypothesis, and it will afterwards be shown that magnetic phenomena appear to result from electrical currents, circulating in magnetic bodies ; a mode of view which connects the theory of magnetism with that of electricity.

620. **Precise definition of poles.**—By the aid of the preceding hypothesis we are enabled to obtain a clearer idea of the distribution of the magnetism in a magnetised bar, and to account for the circumstance that there is no free magnetism in the middle of the bar, and that it is strongest at the poles. If AB (fig. 499) represent a magnet, then the alternate black and white spaces may be taken to represent the position of the magnetic fluids in a series of particles after magnetisation ; in accordance with what

has been said, the white spaces, representing the south fluid, all point in one direction, and the north fluid in the opposite direction. The last half

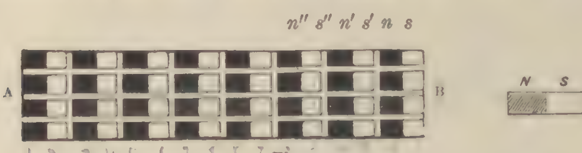


Fig. 499.

of the terminal molecule at one end would have north polarity, and at the other south polarity. Let N represent the north pole of a magnetic needle placed near the magnet AB; then the south fluid, *s*, in the terminal molecule would tend to attract N, and the north fluid *n* would tend to repel it; but as the molecule of south fluid *s* is nearer N than the molecule of north fluid *n*, the attraction between *s* and N would be greater than the repulsion between *n* and N. Similarly the attraction between *s'* and N would be greater than the repulsion between *n'* and N, and so on with the following *s''* and *n''*, etc. And all these forces would give a resultant tending to attract N, whose point of application would have a certain fixed position, which would be the south pole of AB. In like manner it might be shown that the resultant of the forces acting at the other end of the bar would form a north pole, and would hence repel the north pole of the needle, but would attract its south pole.

That such a series of polarised particles really acts like an ordinary magnet may be shown by partly filling a glass tube with steel filings, and passing the pole of a strong magnet five or six times along the outside in one constant direction, taking care not to shake the tube. The individual filings will thus be magnetised, and the whole column of them presented to a magnetic needle will attract and repel its poles just like an ordinary bar magnet, exhibiting a north pole at one end, a south pole at the other, and no polarity in the middle; but on shaking the tube, or turning out the filings, and putting them in again so as to destroy the regularity, every trace of polarity will disappear.

It appears hence that the polarity at each end of a magnet is caused by the fact that the resultant action on a magnetic body is strongest near the ends, and does not arise from an accumulation of the magnetic fluids at the ends.

The same point may be illustrated by the following experiment, which is due to Grove. In a glass tube with flat glass ends is placed water in which is diffused magnetic oxide of iron. Round the outside of the tube is coiled some insulated wire. On looking at a light through the tube the liquid appears dark and muddy, but on passing a current of electricity through the wire it becomes clearer. This is due to the particles setting with their longest dimension parallel to the axis of the tube, in which position they obstruct the passage of light to a less extent.

621. **Experiment with broken magnets.**—That the magnetic fluids are present in all parts of the bar, and not simply accumulated at the ends,

is also evident from the following experiment. A steel knitting-needle is magnetised by friction with one of the poles of a magnet, and then, the existence of the two poles and of the neutral line having been ascertained by means of iron filings, it is broken in the middle. But now, on presenting successively the two halves to a magnet, each will be found to possess two opposite poles and a neutral line, and in fact is a perfect magnet. If these new magnets are broken in turn in two halves, each will be a complete magnet with its two poles and neutral line, and so on, as far as the division can be continued. It is, therefore, concluded by analogy that the smallest parts of a magnet, the ultimate molecules, contain the two fluids.

This experiment proves also that the magnetic fluids are not neutralised, but are simply latent; for if they had been neutralised, they would not have been set at liberty by the separation of the two particles. This property, which we attribute to the two magnetisms, of becoming latent without being previously neutralised, is illustrated in the experiment with the two magnets and a key described in article 618.

622. **Magnetic induction.**—When a magnetic substance is placed in contact with a magnet, the two fluids of the former become separated; and so long as the contact remains, it is a complete magnet, having its two poles and its neutral line. For instance, if a small cylinder of soft iron, *ab* (fig. 500), be placed in contact with one of the poles of a magnet, the cylinder can in turn support a second cylinder; this in turn a third

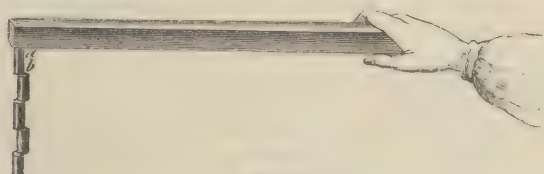


Fig. 500.

and so on, to as many as seven or eight, according to the power of the magnet. Each of these little cylinders is a magnet; if it be the north pole of the magnet to which the cylinders are attached, the part *a* will have south, and *b* north magnetism; *b* will in like manner develop in the nearest end of the next cylinder south magnetism, and so on. But these cylinders are only magnets so long as the influence of a magnetised bar continues. For, if the first cylinder be removed from the magnet, the other cylinders immediately drop, and retain no trace of magnetism. The separation of the two fluids is only momentary, which proves that the magnet yields nothing to the iron. Hence we may have *temporary* magnets as well as *permanent* magnets: the former of iron and nickel, the latter of steel and cobalt. How this difference in action is explained will be shown directly.

This action, in virtue of which a magnet can develop magnetism in iron, is called *magnetic induction* or *influence*, and it can take place without actual contact between the magnet and the iron, as is seen in the

following experiment. A bar of soft iron is held with one end near a magnetic needle. If now the north pole of a magnet be approached to the iron without touching it, the needle will be attracted or repelled, according as its south or north pole is near the bar. For the north pole of the magnet will develop south magnetism in the end of the bar nearest it, and therefore north magnetism at the other end, which would thus attract the south, but repel the north end of the needle. Obviously, if the other end of the magnet were brought near the iron, the opposite effects would be produced on the needle; or if the opposite pole of a second magnet of equal strength simultaneously be brought near the iron, the needle would be unaffected, as one magnet would undo the work of the other.

Among other things, magnetic induction explains the formation of the tufts of iron filings which become attached to the poles of magnets. The parts in contact with the magnet are converted into magnets; these act inductively on the adjacent parts, these again on the following ones, and so on, producing a filamentary arrangement of the filings.

623. **Coercive force.**—We have seen from the above experiments that soft iron becomes instantaneously magnetised under the influence of a magnet, but that this magnetism is not permanent, and ceases when the magnet is removed. Steel likewise becomes magnetised by contact with a magnet, but the operation is effected with difficulty, and the more so as the steel is more highly tempered. Placed in contact with a magnet, a steel bar acquires magnetic properties very slowly, and to make the magnetism complete, the steel must be rubbed with one of the poles. But this magnetism, once evoked in steel, is permanent, and does not disappear when the inducing force is removed.

These different effects in soft iron and steel are ascribed to a *coercive force*, which, in a magnetic substance, offers a resistance to the separation of the two fluids, but which also prevents their recombination when once separated. In steel this coercive force is very great, in soft iron it is very small or almost absent. By oxidation, pressure, or torsion, a certain amount of coercive force may be imparted to soft iron; and by heat, hammering, etc., the coercive force may be lessened, as will be afterwards seen.

624. **Difference between magnets and magnetic substances.**—*Magnetic substances* are substances which, like iron, steel, nickel, are attracted by the magnet. They contain the two fluids, but in a state of neutralisation. Compounds containing iron are usually magnetic, and the more so in proportion as they contain a larger quantity of iron. Some, however, like iron pyrites, are not attracted by the magnet.

A magnetic substance is readily distinguished from a magnet. The former has no poles; if successively presented to the two ends of a magnetic needle, *ab* (fig. 497), it will attract both ends equally, while a magnet would attract the one, but repel the other. Magnetic substances also have no action on each other, while magnets attract or repel each other, according as unlike or like poles are presented.

Iron is not the only substance which possesses magnetic properties;

nickel has considerable magnetic power, but far less than that of iron; cobalt is less magnetic than nickel; while to even a slighter extent chromium and manganese are magnetic. Further, we shall see that powerful magnets exert a peculiar influence on all substances.

CHAPTER II.

TERRESTRIAL MAGNETISM. COMPASSES.

625. **Directive action of the earth on magnets.**—When a magnetised needle is suspended by a thread, as represented in fig. 497, or when placed on a pivot on which it can move freely (fig. 501), it ultimately sets in a position which is more or less north and south. If removed from this position, it always returns to it after a certain number of oscillations.

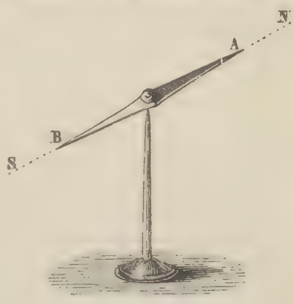


Fig. 501.

Analogous observations have been made in different parts of the globe, from which the earth has been compared to an immense magnet, whose poles are very near the terrestrial poles, and whose neutral line virtually coincides with the equator.

The polarity in the northern hemisphere is called the *northern* or *boreal* polarity, and that in the southern hemisphere the *southern* or *austral* polarity. In French works the end of the needle pointing north is called the *austral* or *southern* pole, and that pointing to the south, the *boreal* or *northern* pole; a designation based on this hypothesis of a terrestrial magnet, and on the law that unlike magnetisms attract each other. In practice it will be found more convenient to use the English names, and call that end of the magnet which points to the north the *north pole*, and that which points to the south the *south pole*. That end of the needle pointing north is in England sometimes spoken of as the *marked end* of the needle.

626. **Terrestrial magnetic couple.**—From what has been stated, it is clear that the magnetic action of the earth on a magnetised needle may be compared to a *couple*, that is, to a system of two equal forces, parallel, but acting in contrary directions.

For let ab (fig. 502) be a moveable magnetic needle making an angle with the magnetic meridian MM' (627). The earth's north pole acts attractively on the marked pole, a, and repulsively on the other pole, b, and two contrary forces are produced, an, and bn', which are equal and parallel; for the terrestrial pole is so distant, and the needle so small, as to justify the assumption that the two directions an and bn' are parallel,

and that the two poles are equidistant from the earth's north pole. But the earth's south pole acts similarly on the poles of the needle, and pro-

Fig. 502.

duces two other forces, *as* and *bs'*, which are also equal and parallel, but the two forces *an* and *as* may be reduced to a single resultant *a*N (33), and the forces *bn'* and *bs'* to a resultant *b*S; these two forces *a*N and *b*S are equal, parallel, and act in opposite directions, and they constitute the *terrestrial magnetic couple*; it is this couple which makes the needle set ultimately in the magnetic meridian, a position in which the two forces N and S are in equilibrium.

The force which determines the direction of the needle thus is neither attractive nor repulsive, but simply directive. If a small magnet be placed on a cork floating in water, it will at first oscillate, and then gradually move into a line which is virtually north and south. But if the surface of the water be quite smooth, the needle will not move either towards the north or towards the south.

If, however, a magnet be approached to a floating needle, attraction or repulsion ensues, according as one or the other of the poles is presented. The reason of the different actions exerted by the earth and by a magnet on a floating needle is as follows:—When the north pole, for instance, of the magnet is presented to the south pole of the needle, the latter is attracted; it is, however, repelled by the south pole of the magnet. Now, the force of magnetic attraction or repulsion decreases with the distance, and as the distance between the south pole of the needle and the north pole of the magnet is less than the distance between the south pole of the needle and the south pole of the magnet, the attraction predominates over the repulsion, and the needle moves towards the magnet. But the earth's magnetic north pole is so distant from the floating needle that its length may be considered infinitely small in comparison, and one pole of the needle is just as strongly repelled as the other is attracted.

627. **Magnetic elements. Declination.**—In order to obtain a full knowledge of the earth's magnetism at any place three essentials are requisite, these are: i. Declination; ii. Inclination; iii. Intensity. These three are termed the *magnetic elements* of the place. We shall explain them in the order in which they stand.

The *geographical meridian* of a place is the imaginary plane passing through this place and through the two terrestrial poles, and the *meridian* is the outline of this plane upon the surface of the globe. Similarly the *magnetic meridian* of a place is the vertical plane passing at this place through the two poles of a moveable magnetic needle in equilibrium about a vertical axis.

In general the magnetic meridian does not coincide with the geographical meridian, and the angle which the magnetic makes with the geographical meridian, or, what is the same thing, the angle which the direction of the needle makes with the meridian, is called the *declination* or *variation of the magnetic needle.* The declination is said to be *east* or *west*, according as the north pole of the needle is to the east or west of the geographical meridian.

628. **Variations in declination.**—The declination of the magnetic needle, which varies in different places, is at present west in Europe and in Africa, but east in Asia and in the greater part of North and South America. It shows further considerable variations even in the same place; these variations are of two kinds; some are regular, and are either secular, annual, or diurnal; others, which are irregular, are called *perturbations.*

Secular variations.—In the same place, the declination varies in the course of time, and the needle appears to make oscillations to the east and west of the meridian, the duration of which is several centuries. The declination has been known at Paris since 1580, and the following table represents the variations which it has undergone:—

Year	Declination	Year	Declination
1580	11° 30′ E.	1825	22° 22′ W.
1663	0	1830	22° 12′ W.
1700	8° 10′ W.	1835	22° 4′ W.
1780	19° 55′ W.	1850	20° 30′ W.
1785	22° W.	1855	19° 57′ W.
1805	22° 5′ W.	1860	19° 32′ W.
1814	22° 34′ W.	1865	18° 44′ W.

This table shows that since 1850 the declination has varied at Paris as much as 34°, and that the greatest declination was attained in 1814, since which time the needle has gradually tended towards the east.

At London, the needle showed in 1580 an east declination of 11° 36′; in 1663 it was at zero; from that time it gradually tended towards the west, and reached its maximum declination of 24° 41′ in 1818; since then it has steadily diminished; it was 22° 30′ in 1850, and is now 20° 2′ W.

The following are the observations of the magnetic elements at Kew for the last six years.

Year	Declination	Inclination	Horizontal Intensity
1865	20° 59′	68° 7′	3·829
1866	20° 51′	68° 6′	3·837
1867	20° 40′	68° 3′	3·844
1868	20° 33′	68° 2′	3·848
1869	20° 25′	68° 1′	3·852
1870	20° 19′	67° 58′	3·857

At Yarmouth and Dover the variation is about 40′ less than at London; at Hull and Southampton about 20′ greater; at Newcastle and Swansea about 1° 15′, and at Liverpool 1° 30′, at Edinburgh 2° 5′, and at Glasgow and Dublin about 2° 25′, greater than at London.

In certain parts of the earth the magnetic coincides with the geographical meridian. These points are connected by an irregularly curved imaginary line, called *a line of no variation*, or *agonic line*. Such a line cuts the east of South America, and, passing east of the West Indies, enters North America near Philadelphia, and traverses Hudson's Bay; thence it passes through the North Pole, entering the Old World east of the White Sea, traverses the Caspian, cuts the east of Arabia, turns then towards Australia, and passes through the South Pole, to join itself again.

Isogonic lines are lines connecting those places on the earth's surface in which the declination is the same. The first of the kind was constructed in 1700 by Halley; as the elements of the earth's magnetism are continually changing, the course of such a line can only be determined for a certain time. One of the newest has been constructed by Captain Evans for the year 1857, and is given in the British Association Report for 1861.

629. **Annual variations.**—Cassini first discovered in 1780 that the declination is subject to small annual variations. At Paris and London it is greatest about the vernal equinox, diminishes from that time to the summer solstice, and increases again during the nine following months. It does not exceed from 15′ to 18′, and it varies somewhat at different epochs.

The *diurnal variations* were first discovered by Graham in 1722; they can only be observed by means of long needles or delicate indicators such as the reflection of a ray of light and very sensitive instruments. In this country the north pole moves every day from east to west from sunrise until one or two o'clock; it then tends towards the east, and at about ten o'clock regains its original position. During the night the needle is almost stationary. Thus the westerly declination is greatest during the warmest part of the day.

At Paris the mean amplitude of the diurnal variation from April to September is from 13′ to 15′, and for the other months from 8′ to 10′. On some days it amounts to 25′, and on others does not exceed 5′. The greatest variation is not always at the same time. The amplitude of the daily variations decreases from the poles towards the equator, where it is very feeble. Thus in the island of Rewak it never exceeds 3′ to 4′.

630. **Accidental variations and perturbations.**—The declination is accidentally disturbed in its daily variations by many causes, such as earthquakes, the *aurora borealis*, and volcanic eruptions. The effect of the aurora is felt at great distances. Auroras which are only visible in the north of Europe act on the needle even in these latitudes, where accidental variations of 20′ have been observed. In polar regions the needle frequently oscillates several degrees; its irregularity on the day before the aurora borealis is a presage of the occurrence of this phenomenon.

Another remarkable phenomenon is the miscellaneous occurrence of magnetic perturbations in very distant countries. Thus Sabine mentions a magnetic disturbance which was felt simultaneously at Toronto, the Cape, Prague, and Van Diemen's Land. Such simultaneous perturbations have received the name of *magnetic storms*.

631. **Declination compass.**—The *declination compass* is an instrument by which the magnetic declination of any place may be measured when its astronomical meridian is known. It consists of a brass box, AB (fig. 503), in the bottom of which is a graduated circle, M. In the centre is a pivot, on which oscillates a very light lozenge-shaped magnetic needle, *ab*.

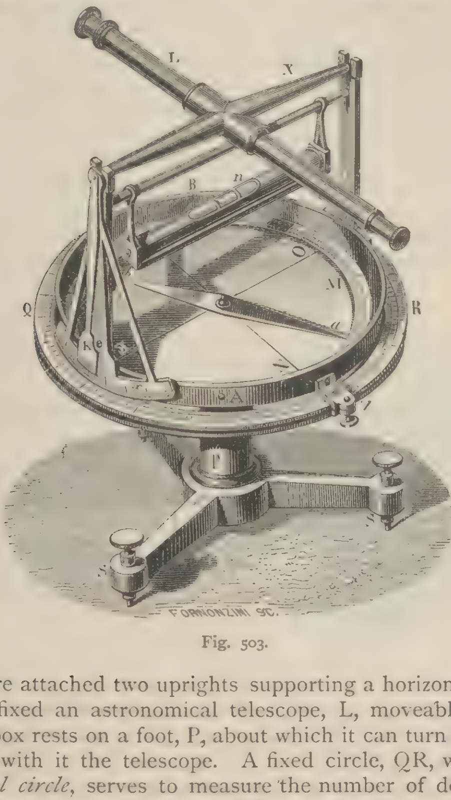


Fig. 503.

To the box are attached two uprights supporting a horizontal axis, X, on on which is fixed an astronomical telescope, L, moveable in a vertical plane. The box rests on a foot, P, about which it can turn in a horizontal plane, taking with it the telescope. A fixed circle, QR, which is called the *azimuthal circle*, serves to measure the number of degrees through which the telescope has been turned, by means of a vernier, V, fixed to the box. The inclination of the telescope, in reference to the horizon, may be measured by another vernier, K, which moves with the axis of the telescope, and is read off on a fixed graduated arc, *x*.

The first thing in determining the declination is to range the compass horizontally by means of the screws, SS, and the level, *n*. The astronomical meridian is then found either by an observation of the sun at noon exactly, or by any of the ready methods known to astronomers. The box, AB, is then turned until the telescope is in the plane of the astronomical meridian. The angle made by the magnetic needle with the diameter, N, which corresponds with the zero of the scale, and is exactly

in the plane of the telescope, is then read off on the graduated limb, and this is east or west, according as the pole, *a*, of the needle stops at the east or west of the diameter, N.

632. **Correction of errors.** These applications of the compass are only correct when the magnetic axis of the needle, that is, the right line passing through the two poles, coincides with its axis of figure, or the line connecting its two ends. This is not usually the case, and a correction must therefore be made, which is done by the method of reversion. For this purpose the needle is not fixed in the cap, but merely rests on it, so that it can be removed and its position reversed; thus what was before the lower is now the upper face. The mean between the observations made in the two cases gives the true declination.

633. **Mariner's compass.** — The magnetic action of the earth has received a most important application in the *mariner's compass*. This is a declination compass used in guiding the course of a ship. Figure 504 represents it enclosed in a rectangular box, placed in a larger box, called

Fig. 504.

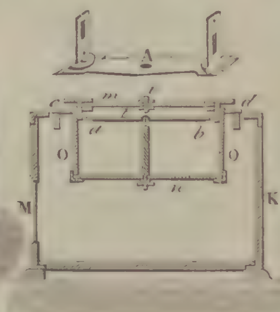


Fig. 505.

the *binnacle*, and which is fixed on the deck in the after part of the vessel. Figure 505 represents a vertical section, and the same letters indicate the same parts in the two figures.

The needle *ab* (fig. 505), which moves very easily on a pivot, is fixed to the lower part of a leaf of mica, *t*, on which is traced a star or rose with 32 branches marking the eight points or *rhumbs* of the wind, the semi-rhumbs and quarters. To keep the compass in a horizontal position, in spite of the rolling of the ship, it is supported on *gimbals*. These are two concentric rings, one of which moves about the axis *cd*, and rests in the box itself, the other moves about the axis *xz*, perpendicular to the first, and fitted in the ring fixed to the axis *cd*.

M is a window of ground glass, by which the compass can be lighted, by means of a lamp placed outside the box. The bottom of the cylindrical box, O, in which is the needle, is of glass, and gives passage to the light, by which the mica plate, *t*, is illuminated. The compass is enclosed by a

second glass, m, and on a pivot, i, in its centre, can be fixed a sight vane, A, when the bearing of the land is to be taken.

Neither the inventor of the compass, nor the exact time of its invention, is known. Guyot de Provins, a French poet of the twelfth century, first mentions the use of the magnet in navigation, though it is probable that the Chinese long before this had used it. The ancient navigators, who were unacquainted with the compass, had only the sun or pole star as a guide, and were accordingly compelled to keep constantly in sight of land for fear of steering in a wrong direction when the sky was clouded.

634. **Inclination. Magnetic equator.**—It might be supposed from the northerly direction which the magnetic needle takes, that the force acting upon it is situated in a point of the horizon : this is not the case, for if the needle be so arranged that it can move freely in a vertical plane about a horizontal axis, it will be seen that, although the centre of gravity of the needle coincides with the centre of suspension, the north pole in our hemisphere dips downwards. In the other hemisphere the south pole is inclined downwards.

The angle which the magnetic needle makes with the horizon, when the vertical plane, in which it moves, coincides with the magnetic meridian, is called the *inclination* or *dip* of the needle. In any other plane than the magnetic meridian, the inclination *increases*, and is 90° in a plane at right angles to the magnetic meridian. For the magnetic inclination is the resultant of two forces, one acting in a horizontal and the other in a vertical plane. When the needle is moved so that it is at right angles to the magnetic meridian, the horizontal component can only

Fig. 506.

act in the direction of the axis of suspension, and, therefore, cannot affect the needle, which is then solely influenced by the vertical component, and stands vertically. The following considerations will make this clearer :—

Let NS (fig. 506) represent a magnetic needle capable of moving in a vertical plane. Let NT represent in direction and intensity the entire force of the earth's magnetism acting on the pole N. Then NT can be resolved into the forces Nh and Nv ; TNh being the angle of inclination or dip.

NT is termed the *total force*, and its components are
Nh, or the *horizontal force*, and
Nv, or the *vertical force*.

Now, it is clear that the greater the angle of dip, TNh, the less becomes Nh, or the horizontal force, and the greater Nv, or the vertical force. Hence, in high latitudes the directive force of a compass, which depends

on the horizontal force, is less than in low latitudes. At the magnetic poles the horizontal force will be *nil*, and the vertical force a maximum; here, therefore, the needle will be vertical. At the magnetic equator the reverse is the case, and the needle will be horizontal. Hence, the oscillations of a *compass* needle, by which, as will presently be explained, the strength of the earth's magnetism is measured, become fewer and fewer as the magnetic poles are approached, although there is really an increase in the total force of the earth.

Again, the reason why a dipping-needle stands vertical when placed E. and W. is clearly because in those positions the horizontal force now acting at right angles to the plane of motion of the needle is ineffectual to move it, and therefore merely produces a pressure on the pivot which supports the needle. But the vertical component of the total force remains unaffected by the new position of the needle. Acting, therefore, entirely alone when the dipping-needle is exactly E. and W., this vertical component drags the needle into a line with itself, that is, 90° from the horizontal plane.

The value of the dip, like that of the declination, differs in different localities. It is greatest in the polar regions, and decreases with the latitude to the equator, where it is approximately zero. In London at the present time the dip is 67° 54′, reckoning from the horizontal line. In the southern hemisphere the inclination is again seen, but in a contrary direction, that is, the south pole of the needle dips below the horizontal line.

The *magnetic poles* are those places in which the dipping-needle stands vertical, that is, where the inclination is 90°. In 1830 the first of these, the terrestrial north pole, was found by Sir James Ross in 96° 43′ west longitude and 70° north latitude. The same observer found in the South Sea, in 76° south latitude and 168° east longitude, that the inclination was 88° 37′. From this and other observations, it has been calculated that the position of the magnetic south pole was at that time in about 154° east longitude and 75½° south latitude.

The line of no declination passes through these poles, and the lines of equal declination converge towards them.

The *magnetic equator* or *aclinic line* is the line which joins all those places on the earth where there is no dip, that is, all those in which the dipping-needle is quite horizontal. It is a somewhat sinuous line, not differing much from a great circle inclined to the horizon at an angle of 12°, and cutting it on two points almost exactly opposite each other, one in the Atlantic, and one in the Pacific. These points appear to be gradually moving their position, and travelling from east to west.

Lines connecting places in which the dipping-needle makes equal angles are called *isoclinic lines.*

The inclination is subject to secular variations, like the declination. At Paris, in 1671, the inclination was 75°; since then it has been continually decreasing, and in 1859 was 66° 14′. In London also the dip has continually diminished since 1720 by about 2·6′ per annum. In 1821 it was 70° 3′; in 1838, 69° 17′; in 1854 it was 68° 31′; in 1859 it was 68° 21′; it

is now (1870) 67° 58′. It is also subject to slight annual and diurnal variations, as we have said; being, according to Hanstein, about 15′ greater in summer than in winter, and 4′ or 5′ greater before noon than after.

635. **Inclination compass.**—An inclination compass is an instrument for measuring the magnetic inclination or dip. It consists of a graduated horizontal brass circle, *m* (fig. 507), supported on three legs, provided

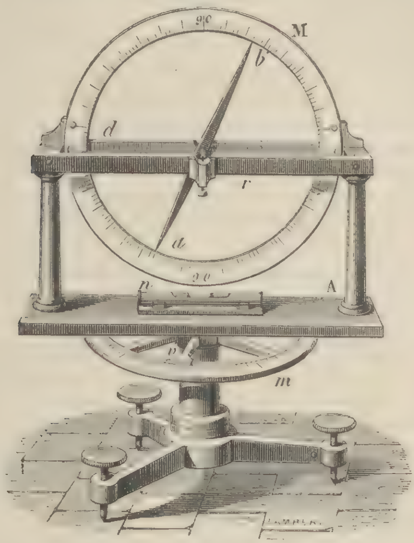


Fig. 507.

with levelling screws. Above this circle there is a plate, A, moveable about a vertical axis, and supporting by means of two columns a second graduated circle, M, which measures the inclination. The needle rests on a frame, *r*, and the diameter passing through the two zeros of the circle, M, can be ascertained to be perfectly horizontal by means of the spirit level, *n*.

To observe the inclination, the magnetic meridian must first be determined, which is effected by turning the plate A on the circle *m*, until the needle is vertical, which is the case when it is in a plane at right angles to the magnetic meridian (634). The plate A is then turned 90° on the circle *m*, by which the vertical circle, M, is brought into the magnetic meridian. The angle, *dca*, which the magnetic needle makes with the horizontal diameter, is the angle of inclination.

There are here several sources of error, which must be allowed for. The most important are three :—i. The magnetic axis of the needle may not coincide with its axis of figure : hence an error, which is corrected by a method of reversion analogous to that already described (632). ii. The

centre of gravity of the needle may not coincide with the axis of suspension, and then the angle, *dca*, is too great or too small, according as the centre of gravity is below or above the centre of suspension; for in the first case the action of gravity is in the same direction as that of magnetism, and in the second is in the opposite direction. To correct this error, the poles of the needle must be reversed by first demagnetising it, and then imparting a contrary magnetism to what it had at first. The inclination is now redetermined, and the mean taken of the results obtained in the two groups of operations. iii. The plane of the ring may not coincide with the true magnetic meridian. It should be in that plane when the needle has its minimum deviation; an observation of this kind should therefore be taken along with that previously described, by which the needle is moved 90° from its maximum deviation.

636. **Astatic needle and astatic system.** An *astatic needle* is one which is uninfluenced by the earth's magnetism. A needle moveable about an axis in the plane of the magnetic meridian and parallel to the inclination would be one of this kind; for the terrestrial magnetic couple acting then in the direction of the axis cannot impart to the needle any determinate direction.

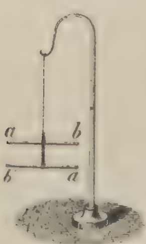


Fig. 508.

An *astatic system* is a combination of two needles of the same force joined parallel to each other with the poles in contrary directions, as shown in figure 508. If the two needles have exactly the same magnetic force, the opposite actions of the earth's magnetism on the poles a' and b and on the poles a and b' counterbalance each other; the system is then completely astatic, and sets at right angles to the magnetic meridian.

A single magnetic needle may also be rendered astatic by placing a magnet near it. By repeated trials a certain position and distance can be found at which the action of the magnet on the needle just neutralises that of the earth's magnetism, and the needle is free to obey any third force.

637. **Intensity of the earth's magnetism.**—If a magnetic needle be moved from its position of equilibrium, it will revert to it after a series of oscillations, which follow laws analogous to those of the pendulum (72). If the magnet be removed to another place, and caused to oscillate during the same length of time as the first, a different number of oscillations will be observed. And the intensity of the earth's magnetism in the two places will be respectively proportional to the squares of the number of oscillations.

If at M the number of oscillations in a minute had been $25 = n$, and at another place, M′, $24 = n'$, we should have—

$$\frac{\text{Intensity of the earth's magnetism at M}}{\text{Intensity of the earth's magnetism at M}'} = \frac{n^2}{n'^2} = \frac{625}{576} = 1{\cdot}085.$$

That is, if the intensity of the magnetism at the second place is taken as unity, that of the first is 1·085. If the magnetic condition of the needle

had not changed in the interval between the two observations, this method would give the relation between the intensities at the two places.

In these determinations of the intensity, it would be necessary to have the oscillations of the dipping-needle, which are produced by the whole force of the earth's magnetism. These, however, are difficult to obtain with accuracy, and, therefore, the oscillations of the declination needle are usually taken. The force which makes the declination needle oscillate is only a portion of the total magnetic force, and is smaller in proportion as the inclination is greater. If the line *ac* (fig. 509) = M represents the total intensity, the angle *i* the inclination, then the horizontal component *ab* is M cos *i*. Hence, to express the intensities in the two places by the oscillations of the declination needle, we must substitute in the preceding equation the values M cos *i* and M′ cos *i*′ for M and M,′ and we have—

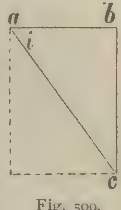


Fig. 509.

$$\frac{M \cos i}{M' \cos i'} = \frac{n^2}{n'^2}; \text{ since } \frac{M}{M'} = \frac{n^2}{n'^2} \frac{\cos i'}{\cos i}.$$

That is to say, having observed in two different places the number of oscillations, n and n', that the same needle makes in the same time, the ratio of the magnetic force in the two places will be found by multiplying the ratio of the square of the number of oscillations by the inverse ratio of the cosine of the angle of inclination.

The magnetic intensity increases with the latitude. Humboldt found a point of minimum intensity on the magnetic equator in Northern Peru. This value is generally taken as the unit to which magnetic intensities at other places are referred, as in the following table :—

Locality	Date	Latitude	Magnetic Intensity
St. Anthony	1802	0·0°	1·087
Carthagena	1801	10·25 N.	1·294
Naples	1805	40·50	1·274
Paris	1800	48·52	1·348
Berlin	1829	52·51	1·366
Petersburg	1828	59·66	1·410
Spitzbergen	1823	79·40	1·567

The lines connecting places of equal intensity are called *isodynamic lines*. They are not parallel to the magnetic equator, but appear to have about the same direction as the isothermal lines.

According to Kuppfer, the intensity appears to diminish at greater heights; a needle which made one oscillation in 24″ vibrated more slowly by 0·01″ at a height of 1000 feet; but, according to Forbes, the intensity is only $\frac{1}{1000}$ less at a height of 3000 feet.

The intensity varies in the same place with the time of day; it attains its maximum between 4 and 5 in the afternoon, and is at its minimum between 10 and 11 in the morning.

It is probable, though it has not yet been ascertained with certainty, that the intensity undergoes secular variations. From measurements of

the total force made monthly at Kew between 1857 and 1862, it appeared that the total force experienced a very slight annual increase.

During the last few years great attention has been devoted to the observation of the magnetic elements, and observatories for this purpose have been fitted up in different parts of the globe. These observations have led to the discovery that the magnetism of the earth is in a state of constant fluctuation, like the waves of the sea. And in studying the variations of the declination, etc., the mean of a great number of observations must be taken, so as to eliminate the irregular disturbances, and bring out the general laws.

The observations made in the English magnet observatories have been reduced by Sabine, and have revealed some curious facts in reference to the magnetic storms. He finds that there is a certain periodicity in their appearance, and that they attain their greatest frequency about every ten years. Independently of this, Schwabe, a German astronomer, who had studied the subject many years, has found that the spots on the sun, seen on looking at it through a coloured glass, vary in their number, size, and frequency, but attain their maximum between every ten or eleven years. Now Sabine has established the interesting fact that the period of their greatest frequency coincides with the period of greatest magnetic disturbance. Other remarkable connections between the sun and terrestrial magnetism have been observed ; one, especially, of recent occurrence, has attracted considerable attention. It was the flight of a large luminous mass across a vast sun spot, and a simultaneous perturbation of the needles in the magnetic observatories ; followed in a few hours by one of the most violent magnetic storms ever known.

CHAPTER III.

LAWS OF MAGNETIC ATTRACTIONS AND REPULSIONS.

638. **Law of decrease with distance.**—Coulomb discovered the remarkable law in reference to magnetism, *that magnetic attractions and repulsions are inversely as the square of the distances.* He proved this by means of two methods :—(i.) that of the torsion balance, and (ii.) that of oscillation.

639. i. **The torsion balance.**—This apparatus depends on the principle that, when a wire is twisted through a certain space, the angle of torsion is proportional to the force of torsion (81). It consists (fig. 510) of a glass case closed by a glass top, with an aperture near the edge, to allow the introduction of a magnet, A. In another aperture in the centre of the top a glass tube fits, provided at its upper extremity with a micrometer. This consists of two circular pieces : *d*, which is fixed, is divided on the edge into 360°, while on *e*, which is moveable, there

is a mark, *c*, to indicate its rotation. D and E represent the two pieces of the micrometer on a larger scale. On E there are two uprights connected by a horizontal axis, on which is a very fine silver wire supporting a magnetic needle, *ab*. On the side of the case there is a graduated scale, which indicates the angle of the needle *ab*, and hence the torsion of the wire.

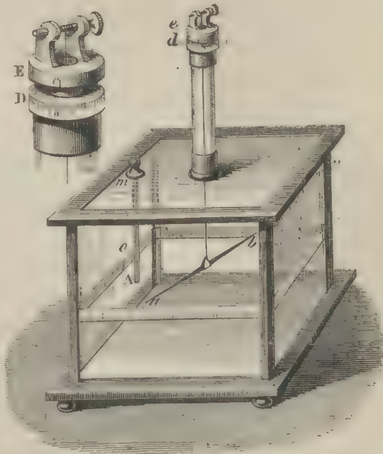


Fig. 510.

When the mark *c* of the disc E is at zero of the scale, D, the case is so arranged that the wire supporting the needle and the zero of the scale in the case are in the magnetic meridian. The needle is then removed from its stirrup, and replaced by an exactly similar one of copper, or any unmagnetic substance; the tube, and with it the pieces D and E, are then turned so that the needle stops at zero of the graduation. The magnetic needle, *ab*, being now replaced, is exactly in the magnetic meridian, and the wire exerts no torsion.

Before introducing the magnet, A, it is necessary to investigate the action of the earth's magnetism on the needle *ab*, when the latter is removed out of the magnetic meridian. This will vary with the dimensions and force of the needle, with the dimensions and nature of the wire, and with the intensity of the earth's magnetism in the place of observation. Accordingly, the piece E is turned until *ab* makes a certain angle with the magnetic meridian. Coulomb found in his experiments that E had to be turned 35° in order to move the needle through 1°; that is, the earth's magnetism was equal to a torsion of the wire corresponding to 35°. As the force of torsion is proportional to the angle of torsion, when the needle is deflected from the meridian by 2, 3 . . . degrees, the directive action of the earth's magnetism is equal 2, 3 . . . times 35°.

The action of the earth's magnetism having been determined, the magnet A is placed in the case so that similar poles are opposite each other. In one experiment Coulomb found that the pole *a* was repelled through 24°. Now the force which tended to bring the needle into the magnetic meridian was represented by $24° + 24 \times 35 = 864$, of which the part 24° was due to the torsion of the wire, and $24 \times 35°$ was the equivalent in torsion of the directive force of the earth's magnetism. As the needle was in equilibrium, it is clear that the repulsive force which counterbalanced those forces must be equal to 864°. The disc was then turned until *ab* made an angle of 12°. To effect this, eight complete rotations of the disc were necessary. The total force which now tended

to bring the needle into the magnetic meridian was composed of: 1st, the 12° of torsion by which the needle was distant from its starting point; 2nd, of $8 \times 360° = 2880$, the torsion of the wire; and, 3rd, the force of the earth's magnetism, represented by a torsion of $12 \times 35°$. Hence, the forces of torsion which balance the repulsive forces exerted at a distance of 24° and of 12° are—

24°	. . . . . .	864
12°	. . . . .	3312

Now, 3312 is very nearly four times 864; hence, for half the distance the repulsive force is four times as great.

640. ii. **Method of oscillations.**—A magnetic needle oscillating under the influence of the earth's magnetism may be considered as a pendulum, and the laws of pendulum motion apply to it. The method of oscillations consists in causing a magnetic needle to oscillate first under the influence of the earth's magnetism alone, and then successively under the combined influence of the earth's magnetism, and of a magnet placed at unequal distances.

The following determination by Coulomb will illustrate the use of the method. A magnetic needle was used which made 15 oscillations in a minute under the influence of the earth's magnetism alone. A magnetic bar about 2 feet long was then placed vertically in the plane of the magnetic meridian, so that its north pole was downwards and its south pole presented to the north pole of the oscillating needle. He found that at a distance of 4 inches the needle made 41 oscillations in a minute, and at a distance of 8 inches 24 oscillations. Now, from the pendulum laws (51), the intensity of the forces are inversely as the squares of the times of oscillations. Hence, if we call M the force of the earth's magnetism, m the attractive force of the magnet at the distance of 4 inches, m' at the distance of 8 inches, we have

$$M : M + m = 15^2 : 41^2, \text{ and}$$
$$M : M + m' = 15^2 : 24^2,$$

eliminating M

$$m : m' = 41^2 - 15^2 : 24^2 - 15^2 = 1456 : 351$$
$$= 4 : 1 \text{ nearly,}$$

or

$$m : m' = 4 : 1.$$

In other words, the force acting at 4 inches is quadruple that which acts at double the distance.

The above results do not quite agree with the numbers required by the law of inverse squares. But this could only be expected to apply in the case in which the repulsive or attractive force is exerted between two points, and not, as is here the case, between the resultant of a system of points. And it is to this fact that the discrepancy between the theoretical and observed results is due.

In the case of the torsion balance, one pole of the magnet to be tested was at so great a distance that it could not appreciably modify the action of the other. When the distance at which two magnets act is large as

compared with their dimensions, the *total action* on one another is nearly inversely as the *third power* of the distances; which, it might be shown, is a necessary consequence of the law that the action of the magnetic elements is inversely as the square of the distance.

When a magnet acts upon a mass of soft iron, the law of the variation with the distance is modified. The attraction in this case is inversely proportional to the distance between the magnet and the iron.

When the distance between the magnet and iron is small, Tyndall has found that the attraction is directly proportional to the square of the strength of the magnet; but when the iron and the magnet are in contact, then the attraction is directly proportional to the strength of the magnet.

CHAPTER IV.

PROCESSES OF MAGNETISATION.

641. **Magnetisation.**—The various sources of magnetism are the influence of natural or artificial magnets, terrestrial magnetism, and electricity. The three principal methods of magnetisation by magnets are known by the technical names of single touch, separate touch, and double touch.

642. **Method of single touch.**—This consists in moving the pole of a powerful magnet from one end to the other of the bar to be magnetised, and repeating this operation several times always in the same direction. The neutral fluid is thus gradually decomposed throughout all the length of the bar, and that end of the bar which was touched last by the magnet is of opposite polarity to the end of the magnet by which it has been touched. This method only produces a feeble magnetic power, and is, accordingly, only used for small magnets. It has further the disadvantage of frequently developing consequent points.

643. **Method of separate touch.**—This method, which was first used by Dr. Knight in 1745, consists in placing the two opposite poles of two magnets of equal force in the middle of the bar to be magnetised, and in moving each of them simultaneously towards the opposite ends of the bar. Each magnet is then placed in its original position, and this operation repeated. After several frictions on both faces the bar is magnetised.

In Knight's method the magnets are held vertically. Duhamel perfected the method by inclining the magnets, as represented in fig. 511; and still more, by placing the bar to be magnetised on the opposite poles of two fixed magnets, the action of which strengthens that of the moveable magnets. The relative position of the poles of the magnets is indicated in the figure.

This method produces the most regular magnets.

644. **Method of double touch.**—In this method, which was invented by Mitchell, the two magnets are placed with their poles opposite each

other in the middle of the bar to be magnetised. But, instead of moving them in opposite directions towards the two ends, as in the method of separate touch, they are kept at a fixed distance by means of a piece of wood placed between them (fig. 511), and are simultaneously moved first towards one end, then from this to the other end, repeating this operation several times, and finishing in the middle, taking care that each half of the bar receives the same number of frictions.

Epinus, in 1758, improved this method by supporting the bar to be magnetised, as in the method of separate touch, on the opposite poles of two powerful magnets, and by inclining the bars at an angle of 15° to 20°.

In practice, instead of two bar magnets it is usual to employ a horseshoe magnet, which has its poles conveniently close together.

By this method of double touch, which is the one generally adopted, powerful magnets are obtained, but they have frequently consequent

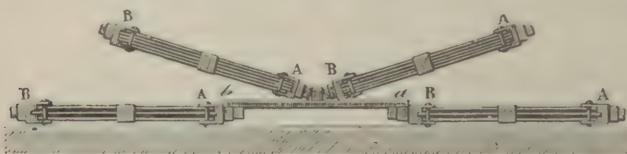


Fig. 511.

points. As this would be a serious injury to compass needles, these are best magnetised by separate touch.

645. **Magnetisation by the action of the earth.**—The action of the earth on magnetic substances resembles that of a magnet, and hence the terrestrial magnetism is constantly tending to separate the two fluids which are in the neutral state in soft iron and in steel. But, as the coercive force is very considerable in the latter substance, the action of the earth is inadequate to produce magnetisation, except when continued for a long time. This is not the case with perfectly soft iron. When a bar of this metal is held in the magnetic meridian parallel to the inclination, the neutral fluid is immediately decomposed, and the bar becomes endowed with feeble magnetic polarity. The lower extremity is a north pole, and if the north pole of a small magnetic needle be approached, it will be repelled. This magnetism is of course unstable, for if the bar be turned, the poles are inverted, as pure soft iron is destitute of coercive force.

While the bar is in this position, a certain amount of coercive force may be imparted to it by giving it several smart blows with a hammer, and the bar retains for a short time the magnetism which it has thus obtained. But the coercive force thus developed is very small, and after a time the magnetism disappears.

If a bar of soft iron be twisted while held vertically, or, better, in the plane of the dip, it acquires a feeble permanent magnetism.

It is this magnetising action of the earth which developes the magnetism frequently observed in steel and iron instruments, such as fire-irons,

rifles, lamp posts, railings, lightning conductors, etc., which remain for some time in a more or less inclined position. They become magnetised with their north pole downward, just as if placed over the pole of a powerful magnet. The magnetism of native black oxide of iron has doubtless been produced by the same causes; the very different magnetic power of different specimens being partly attributable to the different positions of the veins of ore with regard to the line of dip. The ordinary irons of commerce are not quite pure, and possess a feeble coercive force; hence a feeble magnetic polarity is generally found to be possessed by the tools in a smith's shop. Cast-iron, too, has usually a great coercive force, and can be permanently magnetised. The turnings, also, of wrought iron and of steel produced by the powerful lathes of our ironworks are found to be magnetised.

646. **Magnetism of iron ships.**—The inductive action of terrestrial magnetism upon the masses of iron always found in ships exerts a disturbing action upon the compass needle. This *local attraction*, as it is called, may be so considerable as to render the indications of the needle almost useless if it be not guarded against. A full account of the manner in which local attraction is produced, and in which it is compensated, is inconsistent with the limits of this book, but the most important points are the following:—

i. A vertical mass of soft iron in the vessel, say in the bows, would become magnetised under the influence of the earth; in the northern hemisphere, the lower end would be a north pole, and the upper end a south pole; and as the latter may be assumed to be nearer the north pole of the compass needle, it would act upon it. So long as the vessel was sailing in the magnetic meridian this would have no effect; but in any other direction the needle would be drawn out of the magnetic meridian, and a little consideration will show that when the ship was at right angles to the magnetic meridian the effect would be greatest. This *vertical induction* would disappear twice in swinging the ship round, and would be at its maximum twice; hence the deviation due to this cause is known as *semicircular deviation.*

ii. Horizontal masses again, such as deck-beams, are also acted upon inductively by the earth's magnetism, and their induced magnetism exerts a disturbing influence upon the magnetic needle. The effect of this horizontal induction will disappear when the ship is in the magnetic meridian, and also when it is at right angles thereto. In positions intermediate to the above the disturbing influence will attain its maximum. Hence in swinging a ship round there would be four positions of the ship's head in which the influence would be at a maximum and four in which it would be at a minimum. This effect of horizontal induction is accordingly spoken of as *quadrantal deviation.*

The influence of both these causes, vertical and horizontal induction, may be remedied in the process of 'swinging the ship.' This consists in comparing the indications of the ship's compass with those of a standard compass placed on shore. The ship is then swung round in various positions, and by arranging small vertical and horizontal masses of soft

iron in proximity to the steering compass, positions are found for them in which the inductive action of the earth upon them quite neutralises the influence of the earth's magnetism upon the ship; and in all positions of the ship, the compass points in the same direction as the one on shore.

iii. The extended use of iron in ship-building, more especially when the frames are entirely of iron, has increased the difficulty. In the process of building a ship, the hammering and other mechanical operations to which it is subject, while under the influence of the earth's magnetism, will cause it to become to a certain extent permanently magnetised. The distribution of the magnetism, the direction of its magnetic axis, will depend on the position in which it has been built; it may or may not coincide with the direction of the keel. The vessel becomes in short a huge magnet, and will exert an influence of its own upon the compass quite independently of vertical or horizontal induction. This influence is *semicircular*, that is, it disappears when the magnetic axis of the ship is in the magnetic meridian and is greatest at right angles to it. It may be compensated by two permanent magnets placed near the compass in suitable positions found by trial during the process of swinging the ship. Supposing the inherent magnetism of the ship to have the power of drawing the compass a point to the east, the compensating magnets may be so arranged as to tend to draw it a point to the west, and thus keep it in the magnetic meridian. If, however, the inherent magnetism be destroyed, from whatever cause, it is clear that the magnets will now draw it aside a point too much to the west. This is the source of a new difficulty. It has been found that a ship which at the time of sailing was properly compensated would on returning from a long voyage have its compasses over-compensated. The buffeting which the ship had experienced had destroyed its inherent magnetism, and numerous instances are known where the loss of a vessel can be directly traced to this cause. Fortunately, it has been found that after some time a ship's magnetic condition is virtually permanent, and is unaltered by any further wear and tear. The magnetism which it then retains is called its *permanent* magnetism, in opposition to the *sub-permanent* which it loses.

The difficulty of adequately compensating compasses, which is greatly increased by the armour-plated and turret ships now in use, has induced one school to throw over any attempt at correction; but by careful observation of the magnetic condition of a ship, and tabulating the errors to construct a table, by comparing which with the indications of the compass at any one time, the true course can be made out.

In the Royal Navy, the plan now adopted is to combine both methods: compensate the errors to a considerable extent, and then construct a table of the residual errors.

647. **Saturation.**—Experiment has shown that to a certain extent the magnetic force which can be imparted to a bar or needle increases with the power of the magnets used. But there is a limit to the magnetic force which can be imparted to a bar or needle, and when this is attained, the bar is said to be *saturated* or *magnetised to saturation.* A

bar may indeed be magnetised beyond this point, but this is not permanent; it gradually diminishes until it has sunk to the point of saturation.

This is readily intelligible, for the magnetisms once separated tend to reunite, and when their attractive force is equal to that which opposes their saturation, that is, the coercive force of the metal, equilibrium is attained, and the magnet is saturated. Hence, more magnetism ought to be developed in bars than they can retain, in order that they may decline to their permanent state of saturation. To increase the magnetism of an unsaturated bar, a less feeble magnet must not be used than that by which it was originally magnetised.

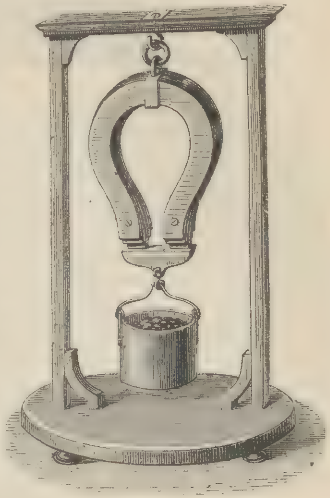


Fig. 512.

648. **Magnetic battery.**—A *magnetic battery* or *magazine* consists of a number of magnets joined together by their similar poles. Sometimes they have the form of a horse-shoe, and sometimes a rectilinear form. The battery represented in fig. 512 consists of five superposed steel plates. That in fig. 513 consists of twelve plates, arranged in three layers of four each. The horse-shoe form is best adapted for supporting a weight, for then both poles are used at once. In both the bars are magnetised separately, and then fixed by screws.

The force of a battery is not equal to the sum of the forces of each bar, owing to the repulsive action exerted by each bar on the adjacent ones. The force is increased by making the lateral plates 1 or 2 centimètres shorter than the one in the middle (fig. 512).

649. **Armatures.**—When even a steel bar is at its limit of saturation, it gradually loses its magnetism. To prevent this, *armatures* or *keepers* are used: these are pieces of soft iron, A and B (fig. 513), which are

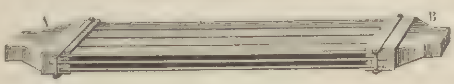


Fig. 513.

placed in contact with the poles. Acted on inductively, they become powerful temporary magnets, possessing opposite polarity to that of the inducing pole, and thus react in turn on the permanent magnetism of the bars, preserving and even increasing it.

When the magnets are in the form of bars, they are arranged in pairs, as shown in fig. 514, with opposite poles in juxtaposition, and the circuit is completed by two small bars of soft iron, AB. Moveable magnetic

needles set spontaneously towards the magnetic poles of the earth, the influence of which acts as a keeper.

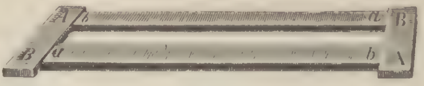


Fig. 514.

A horse-shoe magnet has a keeper attached to it, which is usually arranged so as to support a weight. The keeper becomes magnetised under the influence of the two poles, and adheres with great force; the weight which it can support being much more than double that which a single pole would hold.

In respect to this weight, a singular and hitherto inexplicable phenomenon has been observed. When contact is once made, and the keeper is charged with its maximum weight, any further addition would detach it; but if left in contact for a day, an additional weight may be added without detaching it, and by slightly increasing the weight every day, it may ultimately be brought to support a far greater load than it would originally. But if contact be once broken, the weight it can now support does not much exceed its original charge.

In providing a natural magnet with a keeper, the line joining the two poles is first approximately determined by means of iron filings. Two plates of soft iron (fig. 515), each terminating in a massive shoe, are then applied to the faces corresponding to the poles. Under the influence of the natural magnet, these plates become magnetised, and if the letters A and B represent the position of the poles of the natural magnet, the poles of the armature are *a* and *b*. These armatures, once magnetised, react on the neutral fluid of the natural magnet, decomposing it, and increasing its natural power. Without armatures, natural magnets are very feeble, but armed they can support a weight that gradually increases to a certain limit, which they cannot exceed.

Fig. 515.

650. **Portative Force.**—The *portative force* is the weight which a magnet can support, and numerous experiments have been made upon it by Häcker. He found that the portative force of a saturated horse-shoe magnet, which, by repeatedly detaching the keeper, has become constant, may be represented by the formula

$$P = a\sqrt[3]{p^2},$$

in which P is the portative force of the magnet, p its own weight, and a a coefficient, which varies with the nature of the steel and the mode of magnetising. It follows from this that a magnet which weighs 1,000 ounces only supports 25 times as much as one weighing 8 ounces or $\frac{1}{125}$ as heavy, and 125 such bars would support as much as one which is as

heavy as all together. It appears immaterial whether the section of the bar is quadratic or circular, and the distance of the legs is of inconsiderable moment; it is important, however, that the magnet be suspended vertically, and that the load be exactly in the middle. In Häcker's magnets the value of a was 10·33, while in Logemann's it was 23.

651. **Circumstances which influence the power of magnets.**—All bars do not attain the same state of saturation, for their coercive force varies. Twisting or hammering imparts to iron or steel a considerable coercive force. But the most powerful of these influences is the operation of tempering (86). Coulomb found that a steel bar tempered at dull redness, and magnetised to saturation, made ten oscillations in 93 seconds. The same bar tempered at a cherry-red heat, and similarly magnetised to saturation, only took 63 seconds to make ten oscillations.

Hence, the harder the steel the greater is its coercive force; it receives magnetism with much greater difficulty, but retains it more effectually. Very hard steel bars have, however, the disadvantage of being very brittle, and in the case of long thin bars, a hard tempering is apt to produce consequent points. Compass needles are usually tempered at the blue heat, that is, about 300° C., by which a high coercive force is obtained without great fragility.

Increase of temperature always produces a diminution of magnetic force. If the changes of temperature are small, those of the atmosphere for instance, the magnet is not permanently altered. Kupfer allowed a magnet to oscillate at different temperatures, and found a definite decrease in its power with increased temperature, as indicated by its slower oscillations. In the case of a magnet $2\frac{1}{2}$ inches in length, he observed that with an increase of each degree of temperature the duration of 800 oscillations was 0·4″ longer. If n be the number of oscillations at zero, and n_1 the number at t, then

$$n_1 = n\ (1 - ct),$$

where c is a constant depending in each case on the magnet used. This formula has an important application in the correction of the observations of magnetic intensity which are made at different places and at different temperatures, and which, in order to be comparable, must first be reduced to a uniform temperature.

When a magnet has been more strongly heated, it does not regain its original force on cooling to its original temperature, but when it has been heated to redness, it is demagnetized. This was first shown by Coulomb, who took a saturated magnet, and progressively heated it to higher temperatures, and observed the number of oscillations after each heating. The higher the temperature to which it had been heated the slower its oscillations.

A magnet heated to bright redness loses its magnetism so completely that it is quite indifferent, not only towards iron, but also towards another magnet. Incandescent iron also does not possess the property of being attracted by the magnet. Hence there is in the case of iron a *magnetic limit*, beyond which it is unaffected by magnetism. Such a magnetic

limit exists in the case of other magnetic metals. With *cobalt*, for instance, it is far beyond a white heat, for at the highest temperatures hitherto examined it is still magnetic ; the magnetic limit of *chromium* is somewhat below red heat ; that of *nickel* at about 350° C., and of *manganese* at about 15° to 20° C.

Epinus found that a steel bar could be powerfully magnetised by heating it to redness, and allowing it to cool between the opposite poles of two powerful magnets. A steel bar heated to redness, and then hardened by sudden cooling in the vertical position, retains the magnetism imparted to it by the inductive action of the earth.

652. **Distribution of free magnetism.**—Applying his method of oscillations, Coulomb investigated the distribution of magnetic force in different parts of a magnet. He placed a large magnet in a vertical position in the magnetic meridian ; he then took a small magnetic needle suspended by a thread without torsion, and, having ascertained the number of its oscillations under the influence of the earth's magnetism alone, he presented it to different parts of the magnet. The oscillations were fewer as the needle was nearer the middle of the bar, and when they had reached that position, their number was the same as under the influence of the earth's magnetism alone. He found that with saturated bars of more than 7 inches in length the distribution could always be expressed by a curve whose abscissæ were the distances from the ends of the magnet, and whose ordinates were the force of magnetism at these points.

With magnets of the above dimensions the poles are at the same distance from the end ; Coulomb found the distance to be 1·6 inches in a bar 8 inches long. The same physicist found that, with shorter bars, the distance of the poles from the end is $\frac{1}{6}$ of the length ; thus with a bar of three inches it would be half an inch.

These results presume that the other dimensions of the bar are very small as compared with its length, that it has a regular shape, and is uniformly magnetised. When these conditions are not fulfilled, the positions of the poles can only be determined by direct trials with a magnetic needle. With lozenge-shaped magnets the poles are nearer the middle.

Coulomb found that these lozenge-shaped bars have a greater *directive* force than rectangular bars of the same weight, thickness, and hardness.

BOOK IX.

FRICTIONAL ELECTRICITY.

CHAPTER I.

FUNDAMENTAL PRINCIPLES.

653. **Electricity. Its nature.**—Electricity is a powerful physical agent which manifests itself mainly by attractions and repulsions, but also by luminous and heating effects, by violent commotions, by chemical decompositions, and many other phenomena. Unlike gravity, it is not inherent in bodies, but is evoked in them by a variety of causes, among which are friction, pressure, chemical action, heat, and magnetism.

Thales, six centuries before Christ, knew that when amber was rubbed with silk, it acquired the property of attracting light bodies; and from the Greek form of this word (ἤλεκτρον, *electron*) the term *electricity* has been derived. This is nearly all the knowledge left by the ancients; and it was not until towards the end of the sixteenth century that Dr. Gilbert, physician to Queen Elizabeth, showed that this property was not limited to amber, but that other bodies, such as sulphur, wax, glass, etc., also possessed it in a greater or less degree.

654. **Development of electricity by friction.**—When a glass rod, or a stick of sealing-wax, or shellac, is held in the hand, and rubbed with a piece of flannel or with the skin of a cat, the parts rubbed will be found to have the property of attracting light bodies, such as pieces of silk, wool, feathers, paper, bran, gold leaf, etc., which, after remaining a short time in contact, are again repelled. In order to ascertain whether bodies are electrified or not, instruments called *electroscopes* are used. The simplest of these, the *electric pendulum* (fig. 516), consists of a pith ball attached by means of a silk thread to a glass support. When an electrified body is brought near the pith ball, the latter is instantly attracted, but after momentary contact is again repelled (fig. 517).

A solid body may also be electrified by friction with a liquid or with a gas. In the Toricellian vacuum a movement of the mercury against the sides of the glass produces a disengagement of electric light visible in the dark; a tube exhausted of air, but containing a few drops of mercury, becomes also luminous when agitated in the dark.

If a quantity of mercury in a dry glass vessel be connected with a gold-leaf electroscope by a wire, and a dry glass rod immersed in it, no indications are observed during the immersion, but on withdrawing the rod, the

leaves increasingly diverge, attaining their maximum when the rod leaves the mercury.

Some substances, particularly metals, do not seem capable of receiving the electric excitement. When a rod of metal is held in the hand, and

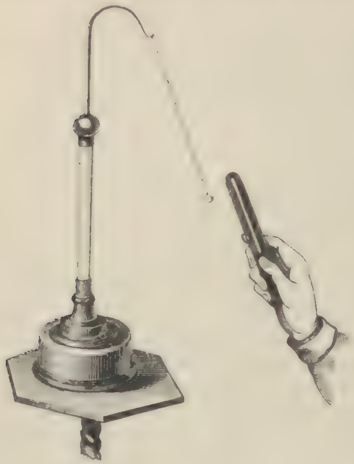


Fig. 516.

Fig. 517.

rubbed with silk or flannel, no electrical effects are produced in it; and bodies were formerly divided into *ideoelectrics*, or those which become electrical by friction, and *anelectrics*, or those which do not possess this property. These distinctions no longer obtain in any absolute sense; it will presently be seen that, under appropriate conditions, all bodies may be electrified by friction (656).

With reference to the cause of the production of electricity by friction nothing is known. Wollaston attributed it to oxidation; but Wilson and Gray have shown that electrical phenomena may be produced in vacuo, and Gay-Lussac proved that electricity may be developed in an atmosphere of carbonic acid.

655. **Conductors and nonconductors.**—When a glass rod, rubbed at one end, is brought near an electroscope, that part only will be electrified which has been rubbed; the other end will produce neither attraction nor repulsion. The same is the case with a rod of shellac or of sealing-wax. In these bodies electricity does not pass from one part to another—they do not *conduct* electricity. Experiment shows, that when a metal has received electricity in any of its parts, the electricity instantly spreads throughout its entire surface. Metals are hence said to be good *conductors* of electricity.

Bodies have, accordingly, been divided into *conductors* and *nonconductors*. This distinction is not absolute, and we may advantageously consider bodies as offering a resistance to the passage of electricity which

varies with the nature of the substance. Those bodies which offer little resistance are then conductors, and those which offer great resistance are nonconductors or insulators : electrical *conductivity* is thus the inverse of electrical *resistance*. We are to consider that between conductors and nonconductors there is a *quantitative* and not a *qualitative* difference; there is no conductor so good but that it offers some resistance to the passage of electricity, nor is there any substance which insulates so completely but that it allows some electricity to pass. The transition from conductors to nonconductors is gradual, and no line of sharp demarcation can be drawn between them.

In this sense we are to understand the following table in which bodies are classed as conductors, semiconductors, and nonconductors : those bodies being conveniently designated as conductors which when applied to a charged electroscope discharge it almost instantaneously; semiconductors being those which discharge it in a short but measurable time, a few seconds, for instance; while nonconductors effect no discharge in the course of a minute.

Conductors.	*Semiconductors.*	*Nonconductors.*
Metals.	Alcohol and ether.	Dry oxides.
Well-burnt charcoal.	Powdered glass.	Ice at $-25°$ C.
Graphite.	Flour of sulphur.	Lime.
Acids.	Dry wood.	Lycopodium.
Aqueous solutions.	Paper.	Caoutchouc.
Water.	Ice at 0°.	Air and dry gases.
Snow.		Dry paper.
Vegetables.		Silk.
Animals.		Diamond and precious stones.
Soluble salts.		Glass.
Linen.		Wax.
Cotton.		Sulphur.
		Resins.
		Amber.
		Shellac.

This list is arranged in the order of decreasing conductivity, or what is the same thing, of increasing resistance. The arrangement is not invariable however. Conductivity depends on many physical conditions. Glass, for example, which does not conduct at any ordinary temperatures, conducts very well at a red heat. Shellac and resin do not conduct so well when they are heated. Water, which is a good conductor, conducts but little in the state of ice at 0°, and very badly at $-25°$. Powdered glass and flour of sulphur conduct very well, while in large masses they are nonconductors; probably because in a state of powder each particle becomes covered with a film of moisture that acts as a conductor.

656. **Insulating bodies. Common reservoir.**—Bad conductors are called *insulators*, for they are used as supports for bodies in which electricity is to be retained. A conductor remains electrified only so long as

it is surrounded by insulators. If this were not the case, as soon as the electrified body came in contact with the earth, which is a good conductor, the electricity would pass into the earth, and diffuse itself through its whole extent. On this account, the earth has been named the *common reservoir*. A body is insulated, by being placed on a support with glass feet, or on a resinous cake, or by being suspended by silk threads. No bodies, however, insulate perfectly; all electrified bodies lose their electricity more or less rapidly by means of the supports on which they rest. Glass is always somewhat hygroscopic, and the aqueous vapour which condenses on it, affords a passage for the electricity; the insulating power of glass is materially improved by coating it with shellac or copal varnish. Dry air is a good insulator, but when the air contains moisture, it conducts electricity, and this is the principal source of the loss of electricity. Hence it is necessary in electrical experiments, to rub the supports with cloths dried at the fire, and to surround electrified bodies by glass vessels, containing substances which attract moisture, such as chloride of calcium.

It is from their great conductivity, that metals do not become electrified by friction. But if they are insulated, and then rubbed, they give good indications. This may be seen by the following experiment (fig. 517). A brass tube is provided with a glass handle, by which it is held,

Fig. 518.

and then rubbed with silk or flannel. On approaching the metal to the pendulum, the pith ball will be attracted. If the metal is held in the hand electricity is indeed produced by friction—but it immediately passes through the body into the ground.

If, too, the cap of a gold-leaf electroscope be briskly flapped with a dry silk handkerchief, the gold leaves will diverge.

657. **Distinction of the two kinds of electricity.**—If electricity be developed on a glass rod by friction with silk, and the rod be brought near an electrical pendulum (fig. 517), the ball will be attracted to the glass, and after momentary contact will be again repelled. By this contact the ball becomes electrified, and so long as the two bodies retain their electricity, repulsion follows when they are brought near each other. If a stick of sealing-wax, electrified by friction with flannel or skin, be approached to another electrical pendulum, the same effects will be produced, the ball will fly towards the wax, and after contact will be repelled. Two bodies, which have been charged with electricity, repel one another. But the electricities, respectively developed in the preceding cases, are not the same. If, after the pith ball has been touched with an electrified glass rod, an electrified stick of sealing-wax, and then an electrified glass rod, be alternately approached to it, the pith ball will be *attracted* by the former and *repelled* by the latter. Similarly, if the pendulum be charged by contact with the electrified sealing-wax, it will be *repelled* when this is approached to it, but *attracted* by the approach of the excited glass rod.

On experiments of this nature, Dufay first made the observation that there are two different electricities : the one developed by the friction of glass, the other by the friction of resin or shellac. To the first the name *vitreous* electricity is given ; to the second the name *resinous* electricity.

658. **Theories of electricity.**—Two theories have been proposed to account for these different effects of electricity. Franklin supposed that there exists a peculiar, subtle, imponderable fluid, which acts by repulsion on its own particles, and pervades all matter. This fluid is present in every body in a quantity peculiar to it, and when it contains this quantity, it is in the natural state, or in a state of equilibrium. By friction, certain bodies acquire an additional quantity of the fluid, and are said to be *positively* electrified : others, by friction, lose a portion, and are said to be *negatively* electrified. The former state corresponds to *vitreous* electricity, and the latter to *resinous* electricity. Positive electricity is represented by the sign +, and negative electricity by the sign – ; a designation based on the algebraical principle, that when a plus quantity is added to an equal minus quantity zero is produced. So when a body containing a quantity of positive electricity is touched with a body possessing an equivalent quantity of negative electricity, a neutral or zero state is produced.

The theory of Symmer, which is now generally admitted, explains in a satisfactory manner most electrical phenomena. But it is only an hypothesis, and must not be accepted as expressing anything absolute.

Symmer's theory assumes that every body contains an indefinite quantity of a subtle imponderable matter, which is called the electrical fluid. This fluid is formed by the union of two fluids –the *positive* and the *negative*. When they are combined they neutralise one another, and the body is then in the natural or neutral state. By friction, and by several other means, the two fluids may be separated, but one of them can never be excited without a simultaneous production of the other. There may, however, be a greater or less excess of the one or the other in any body, and it is then said to be electrified *positively* or *negatively*. As in Franklin's theory, *vitreous* corresponds to *positive*, and *resinous* to *negative* electricity. This distinction is merely conventional : it is adopted for the sake of convenience, and there is no other reason why resinous electricity should not be called positive electricity.

Fluids of the same name repel one another, and fluids of opposite kinds attract each other. The fluids can circulate freely on the surface of certain bodies, which are called conductors, but remain confined to certain parts of others, which are called nonconductors.

As has been already said, this theory is quite hypothetical ; but its general adoption is justified by the convenient explanation which it gives of electrical phenomena.

659. **Action of electrified bodies on each other.**—Admitting the two-fluid hypothesis, the phenomena of attraction and repulsion may be enunciated in the following law, which is the basis of all the theories of frictional electricity :—

Two bodies charged with the same electricity repel each other; two bodies charged with opposite electricities attract each other.

These attractions and repulsions take place in virtue of the action which the two electricities exert on themselves, and not in virtue of their action on the particles of matter.

660. **Law of the development of electricity by friction.**—Whenever two bodies are rubbed together, the neutral fluid is decomposed. Two electricities are developed at the same time and in equal quantities—one body takes the positive, and the other the negative fluid. This may be proved by the following simple experiment devised by Faraday :—A small flannel cap provided with a silk thread is fitted on the end of a stout rod of shellac, and rubbed round a few times. When the cap is removed by means of a silk thread, and presented to a pith-ball pendulum charged with positive electricity, the latter will be repelled, proving that the flannel is charged with positive electricity ; while, if the shellac is presented to the pith ball, it will be attracted, showing that the shellac is charged with negative electricity. Both electricities are present in equal quantities ; for if the rod be presented to the electroscope before removing the cap, no action is observed.

The electricity developed on a body by friction depends on the rubber as well as the body rubbed. Thus glass becomes negatively electrified when rubbed with cat's skin, but positively when rubbed with silk. In the following list the substances are arranged in such an order, that each becomes positively electrified when rubbed with any of the bodies following, but negatively when rubbed with any of those which precede it :

1. Cat's skin.
2. Flannel.
3. Ivory.
4. Rock crystal.
5. Glass.
6. Cotton.
7. Silk.
8. The hand.
9. Wood.
10. Metals.
11. Caoutchouc.
12. Sealing-wax.
13. Resin.
14. Sulphur.
15. Gutta percha.
16. Gun-cotton.

The nature of the electricity set free by the friction depends also on the degree of polish, the direction of the friction, and the temperature. If two glass discs of different degrees of polish are rubbed against each other, that which is most polished is positively, and that which is least polished is negatively electrified. If two silk ribbons of the same kind are rubbed across each other, that which is transversely rubbed is negatively, and the other positively electrified. If two bodies of the same substance, and of the same polish, but of different temperatures, are rubbed together, that which is most heated is negatively electrified. Generally speaking, the particles which are most readily displaced are negatively electrified.

661. **Development of electricity by pressure and cleavage.**—Electrical excitement may be produced by other causes than friction. If a disc of wood, covered with oiled silk, and a metal disc, both provided

with insulating handles, be pressed together, and then suddenly separated, the metal disc is negatively electrified. A crystal of Iceland spar pressed between the fingers becomes positively electrified, and retains this state for some time. The same property is observed in several other minerals, even though conductors, provided they be insulated. If cork and caoutchouc be pressed together, the first becomes positively, and the other negatively electrified. A disc of wood pressed on an orange and separated, carries away a good charge of electricity, if the contact be rapidly interrupted. But if the disc is slowly removed the quantity is smaller, for the two fluids recombine at the moment of their separation. For this reason there is no apparent effect when the two bodies pressed together are good conductors.

Becquerel has also observed that cleavage is a source of electricity. If a plate of mica be rapidly split in the dark, a slight phosphorescence is perceived. Becquerel fixed glass handles to each side of the plate of mica, and then rapidly separated them. On presenting each of the plates thus separated to an electroscope, he found that one was negatively and the other positively electrified.

Laminated mica, and all badly conducting crystalline substances, exhibit electrical indications by cleavage. The separated plates are always in opposite electrical conditions, provided they are not good conductors : for if they were, the separation would not be sufficiently rapid to prevent the recombination of the two electricities. To the phenomena here described is due the luminous appearance seen in the dark when sugar is broken.

662. **Pyroelectricity.**—Certain minerals, when warmed, acquire electrical properties; a phenomenon to which the name *pyroelectricity* is given. It is best studied in tourmaline, in which it was first discovered, from the fact that this mineral had the power of first attracting and then repelling hot ashes when placed among them.

To observe this phenomenon, a crystal of tourmaline is balanced by a silk thread, in a glass cylinder placed on a heated metal plate. On subsequently investigating the electric condition of the ends, by approaching to them successively an electrified glass rod, one end will be found to be positively electrified, and the other end negatively electrified, and each end shows this polarity as long as the temperature rises. The arrangement of the electricity is thus like that of the magnetism in a magnet. The points at which the intensity of free electricity is greatest are called the *poles*, and the line connecting them is the *electric axis*. When a tourmaline, while thus electrified, is broken in the middle, each of the pieces has its two poles.

These polar properties depend on the *change* of temperature. When a tourmaline, which has become electrical by being warmed, is allowed to cool regularly, it first loses electricity, and then its polarity becomes reversed ; that is, the end which was positive now becomes negative, and that which was negative becomes positive, and the position of the poles now remains unchanged so long as the temperature sinks. Tourmaline only becomes pyroelectric within certain limits of temperature ; these

vary somewhat with the length, but are usually between 10° and 150° C. Below and above these temperatures it behaves like any other body, and shows no polarity.

The name *analogous* pole is given to that end of the crystal which shows positive electricity when the temperature is rising, and negative electricity when it is sinking; *antilogous* pole to that end which becomes negative by being heated, and positive by being cooled.

The phenomena of pyroelectricity are intimately connected with the crystalline form of the mineral; and is only seen in those crystals whose forms are *hemihedral*, or which are differently modified at the ends of their crystallographical principal axis.

Besides tourmaline the following minerals are found to be pyroelectric: boracite, topaz, prehnite, silicate of zinc, scolezite, axenite. And the following organic bodies are pyroelectric: cane-sugar, Pasteur's salt (racemate of sodium and ammonium), tartrate of potassium, &c.

CHAPTER II.

QUANTITATIVE LAWS OF ELECTRICAL ACTION.

663. **Laws of electrical attractions and repulsions.**—The laws which regulate the attractions and repulsions of electrified bodies may be thus stated :—

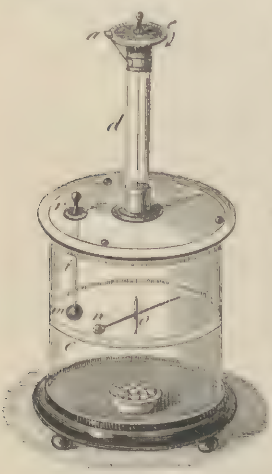


Fig. 519.

I. *The repulsions or attractions between two electrified bodies are in the inverse ratio of the squares of their distance.*

II. *The distance remaining the same, the force of attraction or repulsion between two electrified bodies is directly as the product of the quantities of electricity with which they are charged.*

These laws were established by Coulomb, by means of the torsion balance, used in determining the laws of magnetic attractions and repulsions (639), modified in accordance with the requirements of the case. The wire, on the torsion of which the method depends, is so fine that a foot weighs only $\frac{1}{10}$ of a grain. At its lower extremity there is a fine shellac thread, *no* (fig. 519), at one end of which is a small disc of copper foil, *n*. Instead of the vertical magnetic needle, there is a glass rod, *i*, terminated by a gilt pith ball, *m*, which passes through the aperture *r*. The scale is fixed round the sides of the vessel, and during the experiment the ball *m* is

opposite the zero point. The micrometer consists of a small graduated disc, *e*, moveable independently of the tube, *d*, and of a fixed index, *a*, which shows by how many degrees the disc is turned. In the centre of the disc there is a small button, to which is fixed the wire which supports *no*.

i. The micrometer is moved until the zero point is opposite the index, and the tube *d* is turned until the knob *n* is opposite zero of the graduated circle : the knob *m* is in the same position, and thus presses against *n*. The knob *m* is then removed and electrified, and replaced in the apparatus, through the aperture *r*. As soon as the electrified knob *m* touches *n*, the latter becomes electrified, and is repelled, and after a few oscillations remains constant at a distance, at which the force of repulsion is equal to the force of torsion. In a special experiment Coulomb found the angle of torsion between the two to be 36° ; and as the force of torsion is proportional to the angle of torsion, this angle represents the repulsive force between *m* and *n*. In order to reduce the angle to 18° it was necessary to turn the disc through 126°. The wire was twisted 126° in the direction of the arrow at its upper extremity, and 18° in the opposite direction at its lower extremity, and hence there was a total torsion of 144°. On moving the micrometer in the same direction, until the angle of deviation was $8\frac{1}{2}$°, 567° of torsion were necessary. Hence the whole torsion was $575\frac{1}{2}$°. Without sensible error these angles of deviation may be taken at 36°, 18°, and 9°, and on comparing them with the corresponding angles of torsion 36°, 144°, and 576°, we see that while the first are as

$$1 : \tfrac{1}{2} : \tfrac{1}{4},$$

the latter are as

$$1 : 4 : 16 ;$$

that is, that for a distance $\frac{1}{2}$ as great, the angle of torsion is 4 times as great, and that for a distance $\frac{1}{4}$ as great the repulsive force is 16 times as great.

In experimenting with this apparatus, the air must be thoroughly dry, in order to diminish, as far as possible, loss of electricity. This is effected by placing in it a small dish containing chloride of calcium.

The experiments by which the law of attraction is proved are made in much the same manner, but the two balls are charged with opposite electricities. A certain quantity of electricity is imparted to the moveable ball, by means of an insulated pin, and the micrometer moved until there is a certain angle below. A charge of electricity of the opposite kind is then imparted to the fixed ball. The two balls tend to move together, but are prevented by the torsion of the wire, and the moveable ball remains at a distance, at which there is equilibrium between the force of attraction, which draws the balls together, and that of torsion, which tends to separate them. The micrometer screw is then removed to a greater distance, by which more torsion and a greater angle between the two balls are produced. And it is from the relation which exists between the angle of deflection on the one hand, and the angle which expresses the force of torsion on the other, that the law of attraction has been deduced.

ii. To prove this second law let a charge be imparted to m; n being in contact with it becomes charged and is repelled to a certain distance. The angle of deflection being noted, let the ball m be touched by an insulated but unelectrified ball of exactly the same size and kind; in this way half its charge is removed, and the angle of deflection will now be found to be only half its original amount. In like manner if either m or the moveable body be now again deprived of half its electricity, the deflection will be a quarter of what it originally was, and so on.

The two laws are included in the formula $F = \frac{ee'}{d^2}$, where F is the force; e and e' the quantities of electricity on any two surfaces, and d the distance between them.

664. **Distribution of electricity.**—When an insulated sphere of conducting material is charged with electricity, the electric fluid passes to the surface of the sphere, and forms an extremely thin layer. If, in Coulomb's balance, the fixed ball be replaced by another electrified sphere, a certain repulsion will be observed. If then this sphere be touched with an insulated sphere identical with the first, but in the natural state, the first ball will be found to have lost half its electricity, and only half the repulsion will be observed. By repeating this experiment with spheres of various substances, solid and hollow, but all having the same superficies, the result will be the same, excepting that with imperfectly conducting materials, the time required for the distribution will be greater. From this it is concluded that the distribution of electricity depends on the extent of the surface, and not on the mass, and, therefore, that electricity does not penetrate into the interior, but is confined to the surface. This conclusion is further established by the following experiments:—

Fig. 520.

i. A thin hollow copper sphere provided with an aperture of about an inch (fig. 520), and placed on an insulating support, is charged in the interior with electricity. When the *carrier* or *proof plane* (a small disc of copper foil at the end of a slender glass or shellac rod) is applied to the interior, and then brought near an electroscope, no electrical indications are produced. But if the proof plane is applied to the electroscope after having been in contact with the exterior, a considerable divergence ensues.

ii. A hollow globe, fixed on an insulating support, is provided with two hemispherical envelopes which fit closely, and can be separated by glass handles. The interior is now electrified, and the two hemispheres brought in contact. On then rapidly removing them (fig. 521)

the coverings will be found to be electrified, while the sphere is in its natural condition.

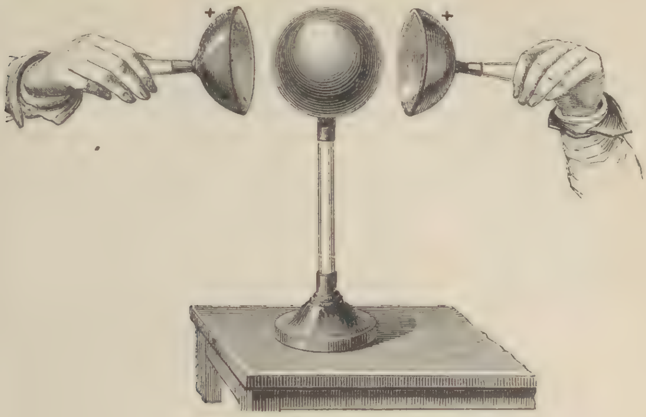


Fig. 521

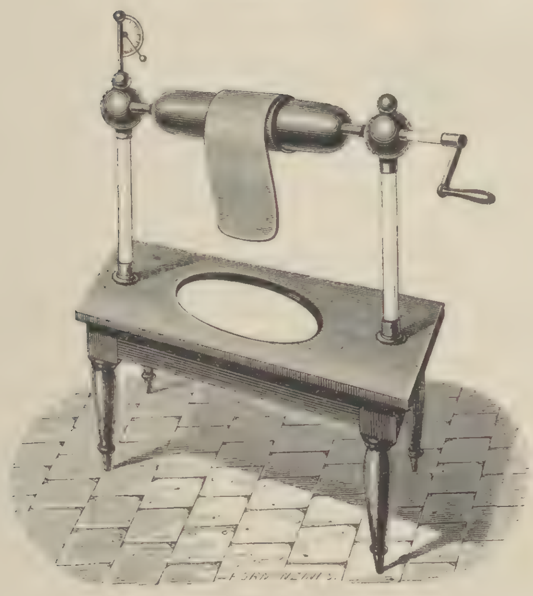


Fig. 522.

iii. The distribution of electricity on the surface may also be shown by means of the following apparatus. It consists of a metallic cylinder on insulated supports, on which is fixed a long strip of tin foil, which can be

rolled up by means of a small insulating handle (fig. 522). A quadrant electrometer is fitted in metallic communication with the cylinder. When the sphere is rolled up, a charge is imparted to the cylinder, by which a certain divergence is produced. On unrolling the tin foil, this divergence gradually diminishes, and increases as it is again rolled up. The quantity of electricity remaining the same, the electrical force, on each unit of surface, is therefore less as the surface is greater.

iv. The following ingenious experiment by Faraday further illustrates this law:—A metal ring is fitted on an insulating support, and a conical gauze bag, such as is used for insects, is fitted to it (fig. 523). By means of a silk thread, the bag can be drawn inside out. After electrifying the bag, it is seen by means of a proof plane that the electricity is on the exterior, but if the positions are reversed by drawing the bag inside out, so that the interior has now become the exterior, the electricity will still be found on the exterior.

Fig. 523.

The property of electricity, of accumulating on the outside of bodies, is ascribed to the repulsion which the particles exert on each other. Admitting the hypothesis of two fluids, and that opposite electricities attract each other in the inverse ratio of their distances, while like electricities repel one another, according to the same law, Poisson, by the aid of mathematical analysis, has arrived at the same conclusion in reference to the distribution of electricity on bodies as that which follows from the previous experiments. Electricity tends constantly to pass to the surface of bodies, where it exists in very thin layers; it continually tends to escape, but is prevented by the resistance of the feebly conducting atmosphere.

665. **Electric tension and density.**—On a metallic sphere the distribution of the electrical fluid will be uniform in every part, simply from its symmetry. This has been demonstrated by means of the proof plane and the torsion balance. A metallic sphere placed on an insulating support was electrified, and touched at different parts of its surface with the proof plane, which each time was applied to the moveable needle of the torsion balance. As in all cases the torsion observed was sensibly the same, it was concluded that the proof plane had each time received the same quantity of electricity. In the case of an elongated ellipsoid (fig. 524) it is found that the electrical layer has a different density at different points of the surface. In virtue of its repulsion the electricity accumulates at the most acute points, and here it has the greatest *tension* or tendency to escape. This is demonstrated by successively touching the ellipsoid at different parts with the proof plane, and then bringing this into the torsion balance. By this means Coulomb found that the greatest deflection was produced when the proof plane had been in contact with the point *a*, and the least by contact with the middle space *c*.

Laplace has found by calculation that the tension at each point is *proportional to the square of the thickness of the electric layer.* The *electric*

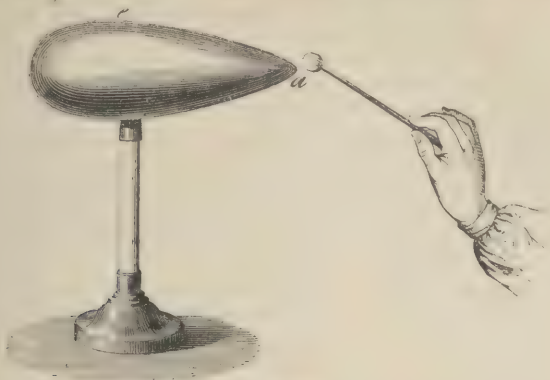


Fig. 524.

density or *electric thickness* is the term used to express the quantity of fluid found at any moment on a given surface. If s represents the surface and Q the quantity of electricity on that surface, then, assuming that the electricity is equally distributed, its electrical density is equal to $\frac{Q}{s}$.

Coulomb found, by quantitative experiments, that in an ellipsoid the density of the electricity at the equator of the ellipsoid is to that at the ends, in the same ratio as the length of the minor to the major axis. On an insulated cylinder, terminated by two hemispheres, the density of the electrical layer at the ends is greater than in the middle. In one case, the ratio of the two densities was found to be as 2·3 : 1. On a circular disc the density is greatest at the edges.

666. **Power of points.**—On a sphere, the electric density is everywhere uniform; the further a body is removed from the shape of a sphere, the more irregular is its accumulation. A pointed rod may be regarded as an elongated ellipsoid, and hence, at its extremity, the electric density will be greatest. But the tension is proportional to the square of the density; and hence the greater the density the greater will be its power of overcoming the resistance of the air, and escaping. If the hand be brought near a point on an electrified conductor a slight wind is felt; and if the disengagement of electricity takes place in the dark a luminous brush is seen. In electrical apparatus, and experiments, frequent use is made of this property of points.

667. **Communication and distribution of electricity on bodies in contact.**—If two conducting bodies, one electrified and the other in the natural state, be brought into contact, the electricity will be equally distributed over the two: the one will lose and the other gain a quantity of electricity proportional to its surface. If the bodies are not conductors, there will only be loss and gain at the points in contact.

By means of the proof plane and the torsion balance, Coulomb made numerous determinations of the distribution of electricity on bodies in contact. When two insulated metallic spheres were placed in contact and electrified, he found that the electric fluid was unequally distributed, and that in proportion to their diameters. The diameters being equal, the electrical density was zero at the point of contact, and only became sensible at 23° from this point: it increased rapidly from 20° to 30°, then more slowly from 60° to 90°, and was almost constant between 60° and 180°.

When the diameters were unequal, and in the ratio of 2 : 1, the density of the point of contact was still zero, but at first increased most rapidly on the large sphere: it then increased more rapidly on the small one, and at 180° from the point of contact its density was greatest on the small one.

668. **Loss of electricity.**—Experience shows that electrified bodies gradually lose their electricity, even when placed on insulating supports. This loss is due to two causes: firstly, to the imperfection of the insulating supports, and, secondly, to the conductivity of the air.

i. All substances conduct electricity in some degree; those which are termed insulators are simply very bad conductors. An electrified conductor resting on supports must, therefore, lose a certain quantity of its electricity.

ii. The loss by the atmosphere varies with the electric tension, with the rapidity with which the air is renewed, and with the hygrometric state.

Dry air is a very imperfect conductor, but when it contains aqueous vapour, it conducts pretty well, and the more moisture it contains, the better it conducts. Coulomb has attempted to show 'that in a still atmosphere, and with a constant hygrometric state, the loss for a very short space of time is directly proportional to the tension:' a law analogous to Newton's law of cooling (377).

Coulomb experimented with moist air. In perfectly dry gases, Matteucci did not find the loss of electricity in accordance with Coulomb's law. He found that within certain limits of tension, the loss was independent of the quantity of electricity, and proportional to the time; in other words, that in equal times there was an equal loss of electricity.

He further found that for equal temperatures and pressures, the loss is the same in air, carbonic acid, and hydrogen, provided they are perfectly dry: at a high tension the loss of negative electricity is greater than that of positive; in dry gases, under a constant pressure, the loss increases with the temperature; and lastly, that in dry gases the loss is independent of the nature of the electrified body; that is, it is the same whether it is a conductor or not.

Coulomb found not only that supports never insulate completely, but that they are the cause of an abundant loss of electricity in bodies strongly electrified. The loss diminishes gradually, and is constant when the tension is low. It may be neglected by giving to the supports an adequate length, which, according to Coulomb, must be proportional to the square of the electric tension of the charged body. Brown shellac is the best insulator; glass is a hygroscopic substance, and must be dried with great

care. It is best covered with a thin layer of shellac varnish, as has already been stated.

669. **Loss of electricity in vacuo.**—Inasmuch as electricity is retained on the surface of bodies by the pressure of the insulating atmosphere, when the pressure diminishes, the loss of electricity increases, and in vacuo, in which resistance is zero, all electricity escapes. This is a necessary consequence of the mathematical theory of electricity, which accounts for the equilibrium of electricity on the surface of bodies. But in opposition to this, Hawksbee, Gray, Snow Harris, and Becquerel have observed, that feeble electrical tensions may be retained in vacuo. Becquerel showed that in a vacuum of a millimeter a body retained a feeble charge for fifteen days. And it is probable, that if an electrified body were in a perfect vacuum, it would retain an electrical charge, provided it were sufficiently removed from any body which could exert upon it an inductive action (670).

CHAPTER III.

ACTION OF ELECTRIFIED BODIES ON BODIES IN THE NATURAL STATE; INDUCED ELECTRICITY. ELECTRICAL MACHINES.

670. **Electricity by influence or induction.**—An insulated conductor, charged with either kind of electricity, acts on bodies in a natural state placed near it, in a manner analogous to that of the action of a magnet on soft iron, that is, it decomposes the neutral fluid, attracting the oppo-

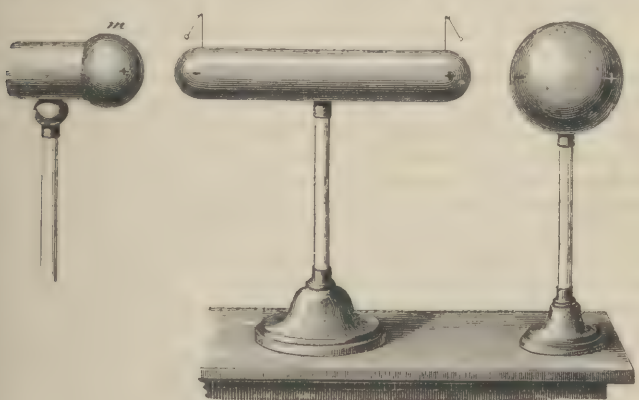


Fig. 525.

site, and repelling the like kind of electricity. The action, thus exerted, is said to take place by *influence* or *induction.*

The phenomena of induction may be demonstrated by means of a brass cylinder placed on an insulating support, and provided at its extremities with two small electric pendulums, which consist of pith balls suspended by linen threads (fig. 525). If this apparatus is placed near an insulated conductor *m*, charged with either kind of electricity, for instance, the conductor of the electrical machine, which is charged with positive electricity, the natural fluid of the cylinder is decomposed, free electricity will be developed at each end, and both pendulums will diverge. If, while they still diverge, a stick of sealing-wax excited by friction with flannel, be approached to that end of the cylinder nearest the conductor, the corresponding pith ball will be repelled, indicating that it is charged with the same kind of electricity as the sealing-wax, that is, with negative fluid; while if the excited sealing-wax is brought near the other ball, it will be attracted, showing that it is charged with positive electricity. If, further, a glass rod, excited by friction with silk, and therefore charged with positive electricity, be approached to the end nearest the conductor, the pendulum will be attracted; while if brought near the other end, the corresponding pendulum will be repelled. If the influence of the charged conductor be suppressed, either by removing it, or placing it in communication with the ground, the separated electricities will recombine, and the pendulums exhibit no divergence. The cause of this phenomenon is obviously a decomposition of the neutral fluid of the cylinder, by the free positive electricity of the conductor, the opposite or negative electricity being attracted to that end of the cylinder nearest the conductor, while the similar electricity is repelled to the other end. Between these two extremities, there is a space destitute of free electricity. This is seen by arranging on the cylinders a series of pairs of pith balls suspended by threads. The divergence is greatest at each extremity, and there is a point at which there is no divergence at all, which is called the *neutral point.* The two fluids, although equal in quantity, are not distributed over the cylinder in a symmetrical manner; the attraction which accumulates the negative electricity at the one end is, in consequence of the greater nearness, greater than the repulsion which drives the positive electricity to the other end, and hence the neutral line is nearer one end than the other. Nor is the electricity induced at the two ends of the cylinder under the same conditions. That which is repelled to the distant extremity is free to escape if a communication be made with the ground, whilst on the other hand, the unlike electricity which is attracted is held bound or captive by the inducing action of the electrified body. Even if contact be made with the ground on the face of the cylinder adjacent to the inducing body, the electricity induced on that face will not escape. The repelled electricity however on the distant surface is not thus bound; it is free to escape by any conducting channel, and hence will immediately disappear, wherever contact be made between the ground and the cylinder. Both the pith balls will collapse, and all signs of electricity on the cylinder depart with the escape of the repelled or free electricity. But now, if communication with the ground be destroyed, and the inducing body be discharged or removed to a considerable dis-

tance, the attracted or bound electricity is itself set free, and diffusing over the whole cylinder causes the pith balls again to diverge, but now with the opposite electricity to that of the original inducing body. The reason for the escape of the repelled electricity is as follows:—If the cylinder be placed in connection with the ground, by metallic contact with the posterior extremity, and the charged conductor be still placed near the anterior extremity, the conductor will exert its inductive action as before. But it is now no longer the conductor alone which is influenced. It is a conductor consisting of the conductor itself, the metallic wire, and the whole earth. The neutral line will recede indefinitely, and since the conductor has become infinite, the quantity of neutral fluid decomposed will be increased. Hence, when the posterior extremity is placed in contact with the ground, the pendulum at the anterior extremity diverges more widely. If the connecting rod be now removed, neither the quantity nor the distribution will be altered; and if the conductor be removed, or be discharged, a charge of negative electricity will be left on the cylinder. It will, in fact, remain charged with electricity, the opposite of that of the charged conductor. Even if, instead of connecting the posterior extremity of the cylinder with the ground, any other part had been so connected, the general result would have been the same. All the parts of the cylinder would be charged with negative electricity, and, on interrupting the communication with the earth, would remain so charged.

Thus a body can be charged with electricity by induction as well as by conduction. But, in the latter case, the charging body loses part of its electricity, which remains unchanged in the former case. The electricity imparted by conduction is of the same kind as that of the electrified body, while that excited by induction is of the opposite kind. To impart electricity by conduction, the body must be quite insulated, while in the case of induction, it must be in connection with the earth at all events momentaneously.

A body electrified by induction acts in turn on bodies placed near it, separating the two fluids in a manner shown by the signs on the sphere.

What has here been said has referred to the inductive action exerted on good conductors. Bad conductors are not so easily acted upon by induction, owing to the great resistance they present to the circulation of electricity, but, when once charged, the electric state is more permanent.

This is analogous to what is met with in magnetism; a magnet instantaneously evokes magnetism in a piece of soft iron, but this is only temporary, and depends on the continued action of the magnet; a magnet magnetises steel with far greater difficulty, but this magnetism is permanent.

671. **Limit to the action of induction.**—The inductive action which an electrified body exerts on an adjacent body in decomposing its neutral fluid is limited. On the surface of the insulated cylinder, which we have considered in the preceding paragraph, let there be at n any small quantity of natural electricity (fig. 526). The positive electricity of the source

m first decomposes by induction the neutral fluid in *n*, attracting its negative fluid towards A, and repelling its positive towards B ; but in the

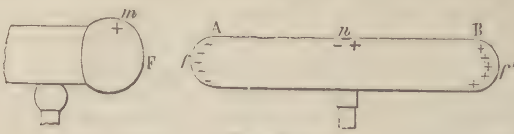


Fig. 526.

degree in which the extremity becomes charged with negative electricity, and the extremity B with positive electricity, there are developed at A and B two forces *f* and *f′*, which act in the opposite direction to the original force. For the forces *f* and *f′* concur in driving towards B the negative fluid of *n*, and towards A its positive fluid. But as the inducing force F which is exerted at *m* is constant, while the forces *f* and *f′* are increasing, a time arrives at which the force F is balanced by the forces *f* and *f′*. All decomposition of the neutral fluid then ceases ; the inducing action has attained its limit.

If the cylinder be removed from the source of electricity, as the inducing action decreases, a portion of the free fluids at A and at B recombine to form the neutral fluid. If, on the other hand, they are brought nearer, as the force F now exceeds the forces *f* and *f′*, a new decomposition of the neutral fluid takes place, and fresh quantities of positive and negative fluids are respectively accumulated at A and B.

672. **Faraday's theory of induction.***—The theory of electricity by induction as just elucidated, is the one hitherto admitted by all physicists. The researches of Faraday on electric polarity tend, however, to modify it, and may, perhaps, lead to overturn it entirely. Hitherto, the influence of the medium, which separates the electrified from the unelectrified body, has been neglected. But Faraday's researches prove that it is in this medium that the inductive actions take place ; and that the inductive action is not an action at a distance, or rather at no distance greater than that between any two molecules. Faraday supposes that, in this medium, successions of layers become alternately positively and negatively electrified.

The following experiment was devised by Faraday to illustrate this *polarisation of the medium*, as he has called it. He placed small filaments of silk in a vessel of turpentine, and, having plunged two conductors in the liquid in opposite sides, he charged one and placed the other in connection with the ground. The particles of silk immediately arranged themselves end to end, and adhered closely together, forming

* 'This theory of Faraday,' remarks M. de la Rive, 'though needing further investigation, deserves the serious attention of physicists. It rests on a sound principle, namely, that electric actions take place through the intervention of material particles, and it tends to bring the electric force into closer connection with other natural forces. One important point follows from Faraday's researches, the fact that the molecular polarisation of insulating bodies is probably also the mode by which electricity is propagated in conductors.'

a continuous chain between the two sides. An experiment by Matteucci also supports Faraday's theory. He placed several thin plates of mica closely together, and provided the outside ones with metallic coatings, like a fulminating pane (694). Having electrified the system, the coatings were removed by insulating handles, and on examining the plates of mica successively, each was found charged with positive electricity on one side, and negative electricity on the other.

On the new view, the action exerted by electrified bodies on bodies in the neutral state, is effected by the polarisation of the alternate layers of air or any other medium. On the old view, the air was supposed to be quite passive, or at most, in virtue of its nonconductivity, to oppose a resistance to the recombination of the two fluids.

Objections have, nevertheless, been raised to Faraday's theory, one of the most formidable of which is the action which electrified bodies exert on others at a distance even in vacuo ; unless, indeed, it be admitted that even in the most perfect vacuum obtainable, sufficient material molecules remain to produce the polarisation. In some researches which Matteucci has recently made on the propagation of electricity in insulators, he has arrived at conclusions differing from those of Faraday.

673. **Specific inductive capacity.**—Faraday names the property which bodies possess of transmitting the electric influence, the *inductive power*. All insulating bodies do not possess it in the same degree. To determine

Fig. 527.

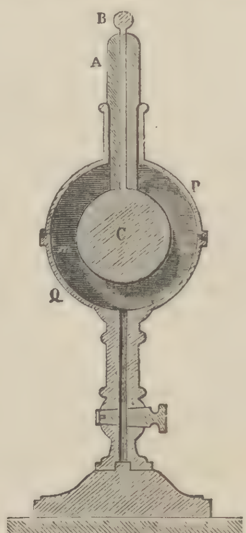


Fig. 528.

and compare the inductive power Faraday uses the apparatus represented in fig. 527, and of which fig. 528 represents a vertical section. It consists

of a brass sphere made up of two halves, P and Q, which fit accurately into each other, like the Magdeburg hemispheres. In the interior of this spherical envelope, there is a smaller brass sphere, C, connected with a metallic rod, terminating in a ball, B. The rod is insulated from the envelope. PQ, by a thick layer of shellac, A. The space *mn* receives the substance whose inductive power is to be determined. The foot of the apparatus is provided with a screw and stopcock, so that it can be screwed on the air pump, and the air in *mn* either rarefied or exhausted.

Two such apparatus perfectly identical are used, and at first they only contain air. The envelopes PQ are connected with the ground, and the knob B of one of them receives a charge of electricity. The sphere C thus becomes charged like the inner coating of a Leyden jar (694). The layer *mn* represents the insulator which separates the two coatings. By touching B with the proof plane, which is then applied to the torsion balance, the quantity of free electricity is measured. In one experiment Faraday observed a torsion of 250°, which represented the free electricity on B. The knob B was then placed in metallic connection with the knob B′ of the other apparatus, and the torsion was now found to be 125°, showing that the electricity had become equally distributed on the two spheres, as might have been anticipated, since the pieces of apparatus were quite equal and each contained air in the space *mn*.

This experiment having been made, the space *mn* in the second apparatus was filled with the substance whose inductive power was to be determined; for example, shellac. The other apparatus, in which *mn* is filled with air, having been charged, the tension of the free electricity on C was measured. Let it be taken at 290°, the number observed by Faraday, in a special case. When the knob B of the first apparatus was connected with the knob B′ of the second, the tension was not found to be 145° as would be expected. The apparatus containing air exhibited a tension of 114°, and that with shellac of 113°. Hence the former had lost 176°, and had retained 114°, while the latter ought to have exhibited a tension of 176° instead of 113°. The second apparatus had taken more than half the charge, and hence a larger quantity of electricity had been dissimulated by the shellac. Of the total quantity of electricity, the shellac had taken 176°, and the air 114°; hence the specific inductive capacity of air is to that of shellac as 114 : 176, or as 1 : 1·55. That is, the inductive power of shellac is more than half as great again as air.

Comparing together other substances by this general method, but varying the details, Faraday and Harris have obtained the following values for the specific inductive capacity of *dielectrics*, as they are called in opposition to *anelectrics* or conductors :—

Air	1·00	Wax	1·86
Spermaceti . . .	1·45	Glass	1·90
Resin	1·76	Shellac	2·00
Pitch	1·80	Sulphur	2·24

By the following simple experiment the influence of the dielectric may

be shown. At a fixed distance above a gold-leaf electroscope, let an electrified sphere be placed by which a certain divergence of the leaves is produced. If now, the charges remaining the same, a disc of sulphur or of shellac be interposed, the divergence increases, showing that inductive action takes place through the sulphur to a greater extent than through a layer of air of the same thickness.

In treating on induction produced by the voltaic battery some experiments of Matteucci will be adduced, which show that the inductive action of current electricity is independent of the nature of the insulator placed between the inducing and the induced body, a result which, of course, does not agree with the experiments of Faraday on frictional electricity.

Faraday finds that all gases have the same inductive capacity, and that this is independent of the temperature and pressure.

674. **Communication of electricity at a distance.**—In the experiment represented in figure 525 the opposite electricities of the conductor, and that of the separated cylinder, tend to unite, but are prevented by the resistance of the air. If the tension is increased, or if the distance of the bodies be diminished, the opposed electricities at length overcome this obstacle ; they rush together and combine, producing a spark, accompanied by a sharp sound. The negative electricity separated on the cylinder, being thus neutralised by the positive electricity of the charged body, a charge of positive electricity remains on the cylinder. The same phenomenon is observed when a finger is presented to a strongly electrified conductor. The latter decomposes by induction the neutral electricity of the body, the opposite electricities combine with the production of a spark, while the electricity of the same kind as the electrified conductor, which is left on the body, passes off into the ground.

The striking distance varies with the tension, the shape of the bodies, their conducting power, and with the resistance and pressure of the interposed medium.

675. **Motion of electrified bodies.**—The various phenomena of attraction and repulsion which are among the most frequent manifestations of electrical action, may all be explained by means of the laws of induction. If M (fig. 529) be a fixed insulated conductor charged with positive electricity, and N be a moveable insulated body, for instance, an electrical pendulum, there are three cases to be considered :—

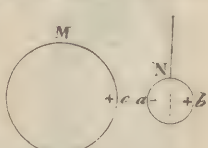


Fig. 529.

i. *The moveable body is unelectrified, and is a conductor.* In this case M acting inductively on N, attracts the negative and repels the positive fluid, so that the maximum of tension is respectively at the points a and b. Now a is nearer c than it is to b, and since attractions and repulsions are inversely as the square of the distance, the attraction between a and c is greater than the repulsion between b and c, and, therefore, N will be attracted to M by a force equal to the excess of the attractive over the repulsive force.

ii. *The moveable body is a conductor, and is electrified.* If the electricity of the moveable body is different from that of the fixed body, there is

always attraction, but if they are of the same kind there is at first repulsion and afterwards attraction. This anomaly may be thus explained: Besides its charge of electricity, the moveable body contains neutral fluid. This is decomposed by the induction of the positive fluid on M, and, consequently, the hemisphere *b* obtains an additional supply of positive electricity, while *a* becomes charged with negative electricity. There is thus attraction and repulsion, as in the foregoing case. The force of repulsion is at first greater, because the quantity of positive fluid on N is greater than that of negative fluid; but the distance *a c* diminishing, the attractive force increases more rapidly than the repulsive force, and finally exceeds it.

iii. *The moveable body is a bad conductor.* If N is charged, repulsion or attraction takes place, according as the electricity is of the same or opposite kind to that of the fixed body. If it is in the natural state, since a powerful and permanent source of electricity can more or less decompose the neutral fluid even in bad conductors, the body M will decompose the neutral fluid of N, and attraction will take place as in the first case.

676. **Gold-leaf electroscope.**—The name *electroscope* is given to instruments for detecting the presence, and determining the kind, of electricity in any body. The original pith ball pendulum is an electroscope; but, though sometimes convenient, it is not sufficiently delicate. Many successive improvements have been made on it, and have resulted in the form now generally used, which is due to Bennett.

Bennett's, or the gold-leaf electroscope. This consists of a tubulated glass shade (fig. 539) standing on a metallic foot which thus communicates with the ground. A metal rod terminating at its upper extremity in a knob, and holding at its lower end two narrow strips of gold leaf, fits in the tubulure of the shade, the neck of which is coated with an insulating varnish. The air in the interior is dried by quicklime, or by chloride of calcium, and on the insides of the shade there are two strips of gold leaf communicating with the ground.

Fig. 539.

When the knob is touched with a body charged with either kind of electricity, the leaves diverge; usually, however, the apparatus is charged by induction thus:—

If an electrified body, a stick of sealing wax, for example, be brought near the knob, it will decompose the natural electricity of the system, attracting to the knob the electricity of the opposite kind and retaining it there, and repelling the electricity of the same kind to the gold leaves, which consequently

diverge. In this way, the presence of an electrical charge is ascertained, but not its quality.

To ascertain the kind of electricity the following method is pursued:—If, while the instrument is under the influence of the body A, which we will suppose has a negative charge, the knob be touched by the finger, the negative electricity decomposed by induction passes off into the ground, and the previously divergent leaves will collapse: there only remains positive electricity retained in the knob by induction from A. If now the finger be first removed, and then the electrified body, the positive electricity previously retained by A will spread over the system, and cause the leaves to diverge. If now, while the system is charged with positive electricity, a positively electrified body, as, for example, an excited glass rod, be approached, the leaves will diverge more widely: for the electricity of the same kind will be repelled to the extremities. If, on the contrary, an excited shellac rod be presented, the leaves will tend to collapse, the electricity, with which they are charged, being attracted by the opposite electricity. Hence we may ascertain the kind of electricity, either by imparting to the electroscope electricity from the body under examination, and then bringing near it a rod charged with positive or negative electricity; or the electroscope may be charged with a known kind of electricity, and the electrified body in question brought near the electroscope.

It has been proposed to use the electroscope as an *electrometer* or measurer of electricity, by measuring the angle of divergence of the leaves. This is done by placing behind them a graduated scale. There are, however, many objections to such a use, and it is rarely employed for this purpose.

ELECTRICAL MACHINES.

677. **Electrophorus.**—It will now be convenient to describe the various electrical machines, or apparatus, for generating and collecting large supplies of statical electricity. One of the most simple and inexpensive of these is the *electrophorus*, which was invented by Volta. Its operation, like that of all other electric machines, depends on the action of induction, of which it forms an excellent illustration. It consists of a cake of resin, B (fig. 532), say about 12 inches diameter, and an inch thick, which is placed on a metallic surface, or very frequently fits in a wooden mould lined with tinfoil, which is called the *form*. Besides this, there is a metal disc, A (fig. 532), of a diameter somewhat less than that of the cake, and provided with an insulating glass handle. The mode of working this apparatus is as follows: All the parts of the apparatus having been well warmed, the cake, which is placed in the form, or rests on a metallic surface, is briskly flapped with silk or flannel, or, better, a catskin, by which it becomes charged with negative electricity. The cover is then placed on the cake. Owing, however, to the minute rugosities of the surface of the resin the cover only comes in contact with a few points, and, from the nonconductivity of the resin, the negative

electricity of the cake does not pass off to the cover. On the contrary, it acts by induction on the neutral electricity of the cover and decomposes

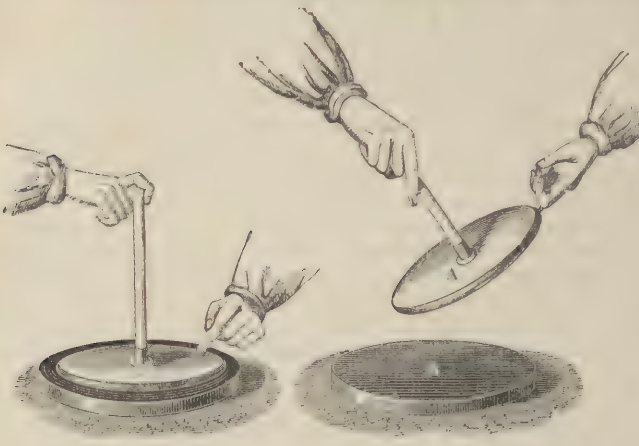


Fig. 531. Fig. 532.

it, attracting the positive electricity to the under surface, and repelling the negative electricity to the upper. If the upper surface be now touched with the finger, the negative electricity, because repelled and free, passes off, and the cover remains charged with positive electricity, held, however, by the negative electricity of the cake; the two electricities do not unite, in consequence of the nonconductivity of the cake (fig. 531). If now the cover be raised by its insulating handle, the charge diffuses itself over the surface, and, if a conductor be brought near it, a smart spark passes.

The metallic form on which the cake rests plays an important part in the action of the electrophorus, as it increases the quantity of electricity, and makes it more permanent. For the negative electricity of the upper surface of the resin acting inductively on the neutral electricity of the lower, decomposes it, retaining on the under surface the positive electricity, while the negative electricity passes of into the ground. The positive electricity thus developed on the under surface reacts on the negative electricity of the upper surface, binding it, and causing it to penetrate into the badly conducting mass, on the surface of which fresh quantities of electricity can be evoked, far beyond the limits possible without the action of the form. It is for this reason that the electrophorus, once charged, retains its state for a considerable time, and sparks can be taken from it even after a long interval. If the form be insulated, the charge obtained is far less than if it is on a conducting support. For the negative electricity developed by induction on the lower surface being now unable to escape, the condensing action referred to cannot take place, and only a feeble charge can be given to the resin. The retention

of electricity is greatly promoted by keeping the cake in the form, and placing the cover upon it, by which the access of air is hindered. Instead of a cake of resin, a disc of gutta percha, or vulcanised cloth, or vulcanite, may be substituted ; and of course, if glass, or any material which becomes positively electrified by friction, be used, the cover acquires a negative charge. 'The electrophorus is a good instance of the conversion of work into electro-potential energy. When the cover is lifted from the excited cake, work must be expended in order to overcome the attraction of the electricity in the cake, for the opposite electricity developed by induction on the cover ; and the equivalent of this work appears in the form of the electricity thus detached. Thus, when a Leyden jar is charged either by the machine or by the electrophorus, the energy of the charge is a transformation of the work of the operator.'—TAIT.

678. **Plate electrical machine.**—The first electrical machine was

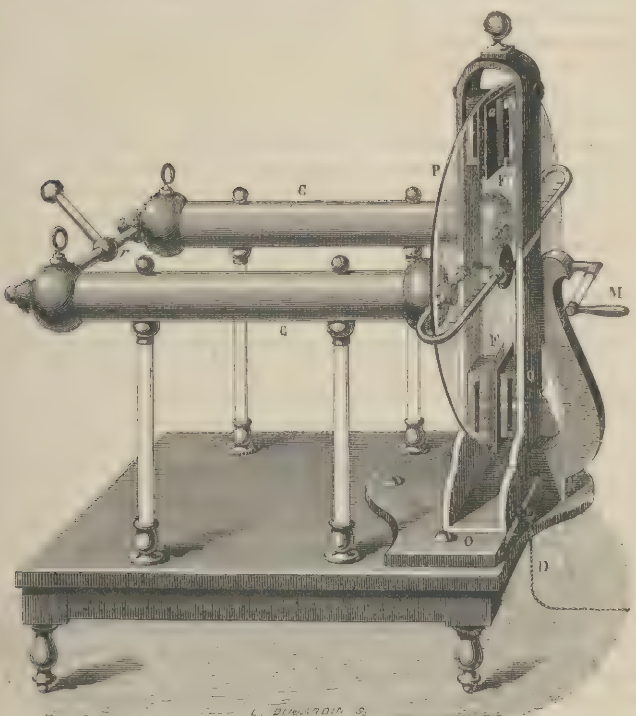


Fig. 533.

invented by Otto von Guericke, the inventor also of the air pump. It consisted of a sphere of sulphur which was turned on an axis by means

of the hand, while the other, pressing against it, served as a rubber. Resin was afterwards substituted for the sulphur, which, in turn, Hawksbee replaced by a glass cylinder. In all these cases the hand served as rubber; and Winckler, in 1740, first introduced cushions of horsehair, covered with silk, as rubbers. At the same time Bose collected electricity, disengaged by friction, on an insulated cylinder of tin plate. Lastly, Ramsden, in 1760, replaced the glass cylinder by a circular glass plate, which was rubbed by cushions. The form which the machine has now is but a modification of Ramsden's original machine.

Between two wooden supports (fig. 533) a circular glass plate, P, is suspended by an axis passing through the centre, and which is turned by means of a glass handle, M. The plate revolves between two sets of *cushions* or *rubbers*, F, of leather or of silk, one set above the axis and one below, which, by means of screws, can be pressed as tightly against the glass as may be desired. The plate also passes between two brass rods shaped like a horse-shoe, and provided with a series of points in the sides opposite the glass: these rods are fixed to larger metallic cylinders, C, which are called the prime *conductors*. The latter are insulated by being supported on glass feet, and are connected with each other by a smaller rod, *r*.

The action of the machine is founded on the excitation of electricity by friction, and on the action of induction. By friction with the rubbers, the glass becomes positively, and the rubbers negatively electrified. If now the rubbers were insulated, they would receive a certain charge of negative electricity which it would be impossible to exceed, for the tendency of the proposed electricities to reunite would be equal to the power of the friction to decompose the neutral fluid. But the rubbers communicate with the ground by means of a chain, and, consequently, as fast as the negative electricity is generated, its tension is reduced to zero by contact with the ground. The positive electricity of the glass acts then by induction on the conductor, attracting the negative electricity. This negative electricity collects in the points opposite to the glass. Here its tension or tendency to discharge becomes so high that it passes across the intervening space of air, and neutralises the positive electricity on the glass. The conductors thus lose their negative electricity, and remain charged with positive electricity. The plate accordingly gives up nothing to the prime conductors; in fact, it only abstracts from them their negative electricity.

If the hand be brought near the conductor when charged, a spark follows, which is renewed as the machine is turned. In this case, the positive electricity decomposes the neutral fluid of the body, attracting its negative electricity, and combining with it when the two have a sufficient tension. Thus, with each spark, the conductor reverts to the neutral state, but becomes again electrified as the plate is turned.

679. **Precautions in reference to the machine.**—The glass, of which the plate is made, must be as little hygroscopic as possible. Of late ebonite has been frequently substituted for glass; it has the advantage of being neither hygroscopic nor fragile, and of readily becoming electri-

cal by friction. The plate is usually from $\frac{1}{12}$ to $\frac{1}{5}$ of an inch in thickness, and from 20 to 30 inches in diameter, though these dimensions are not unfrequently exceeded.

The rubbers require great care, both in their construction and in their preservation. They are commonly made of leather, stuffed with horsehair. Before use they are coated either with powdered *aurum musivum* (sulphuret of tin), or graphite, or amalgam. The action of these substances is not very clearly understood. Some consider that it merely consists in promoting friction. Others, again, believe that a chemical action is produced, and assign, in support of this view, the peculiar smell noticed near the rubbers when the machine is worked. Amalgams, perhaps, promote most powerfully the disengagement of electricity. *Kienmayer's amalgam* is the best of them. It is prepared as follows : one part of zinc and one part of tin are melted together, and removed from the fire and two parts of mercury stirred in. The mass is transferred to a wooden box containing some chalk, and then well shaken. The amalgam, before it is quite cold, is powdered in an iron mortar, and preserved in a stoppered glass vessel. For use, a little cacao butter or lard is spread over the cushion, some of the powdered amalgam sprinkled over it, and the surface smoothed by a ball of flattened leather.

In order to avoid a loss of electricity, two quadrant-shaped pieces of oiled silk are fixed to the rubbers, so as to cover the plate on both sides, one at the upper part from *a* to F, and the other in the corresponding part of the lower rubbers. These flaps are not represented in the figure. Yellow oiled silk is the best, and there must be perfect contact between the plate and the cloth.

Ramsden's machine, as represented in fig. 533, only gives positive electricity. But it may be arranged so as to give negative electricity by placing it on a table with insulating supports. By means of a chain, the conductor is connected with the ground, and the machine worked as before. The positive electricity passes off by the chain into the ground, while the negative electricity remains in the supports and in the insulated table. On bringing the finger near the uprights, a sharper spark than the ordinary one is obtained.

680. **Maximum of tension.**—It is impossible to exceed a certain limit of electrical tension with the machine, whatever precautions are taken, or however rapidly the plate is turned. This limit is attained when the loss of electricity equals its production. The loss depends on three causes : i. The loss by the atmosphere, and the moisture it contains ; this is proportional to the tension. ii. The loss by the supports. iii. The recombination of the electricities of the rubbers and the glass.

The first two causes have been already mentioned. With reference to the latter, it must be noticed that the electrical tension increases with the rapidity of the rotation, until it reaches a point at which it overcomes the resistance presented by the nonconductivity of the glass. At this point, a portion of the two electricities separated on the rubbers and on the glass recombines, and the tension remains constant. It is, therefore, ultimately independent of the rapidity of rotation.

681. **Quadrant electrometer.**—The electric tension is measured by the *quadrant* or *Henley's electrometer*, which is attached to the conductor. This is a small electric pendulum, consisting of a wooden rod, *d*, to which is attached an ivory or cardboard scale, *c* (fig. 534). In the centre of this is a small whalebone index, moveable on an axis, and terminating in a pith ball, *a*. Being attached to the conductor, the index rises as the machine is charged, ceasing to rise when the limit is attained. When the rotation is discontinued the index falls rapidly if the air is moist, but in dry air it only falls slowly, showing, therefore, that the loss of electricity in the latter case is less than in the former.

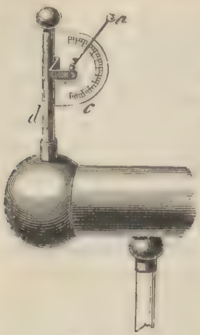


Fig. 534.

682. **Cylinder electrical machine.**—The construction of the cylinder machines, as ordinarily used in England, is due to Nairne. They are well adapted for obtaining either kind of electricity. In Nairne's machine (fig. 535) the cylinder is rubbed by only one cushion, C, which is made of leather stuffed with horsehair, and is screwed to an insulated conductor, A. On the opposite side of the cylinder, there is a similar insulated con-

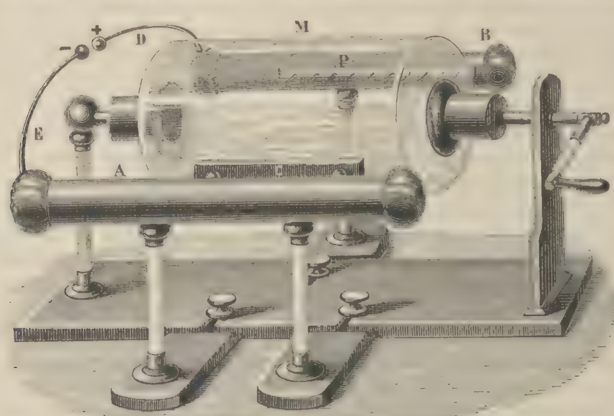


Fig. 535.

ductor, B, provided with a series of points on the sides next the glass. To the lower part of the cushion C is attached a piece of oiled silk, which extends over the cylinder to just above the points. This is not represented in the figure. When the cylinder is turned, A becomes charged with negative and B with positive electricity by the loss of its negative from the points P. The two opposite electricities will now unite by a succession of sparks across D and E. If use be made of the electricity, either the rubber or the prime conductor must be connected with the

ground. In the former case positive electricity is obtained, in the latter negative.

683. **Armstrong's hydro-electric machine.**—In this machine electricity is produced by the disengagement of aqueous vapour through narrow orifices. The discovery of the machine was occasioned by an accident. A workman having accidentally held one hand in a jet of steam, which was issuing from an orifice in a steam boiler at high pressure, while his other hand grasped the safety valve, was astonished at experiencing a smart shock. Sir W. Armstrong (then Mr. Armstrong, of Newcastle), whose attention was drawn to this phenomenon, ascertained that the vapour was charged with positive electricity, and by repeating the experiment with an insulated locomotive, found that the boiler was negatively charged. Armstrong believed that the electricity was due to a sudden expansion of the vapour; Faraday, who afterwards examined the question, ascertained its true cause, which will be best understood after describing a machine which Armstrong devised for reproducing the phenomenon.

It consists of a boiler of wrought-iron plate (fig. 536), with a central

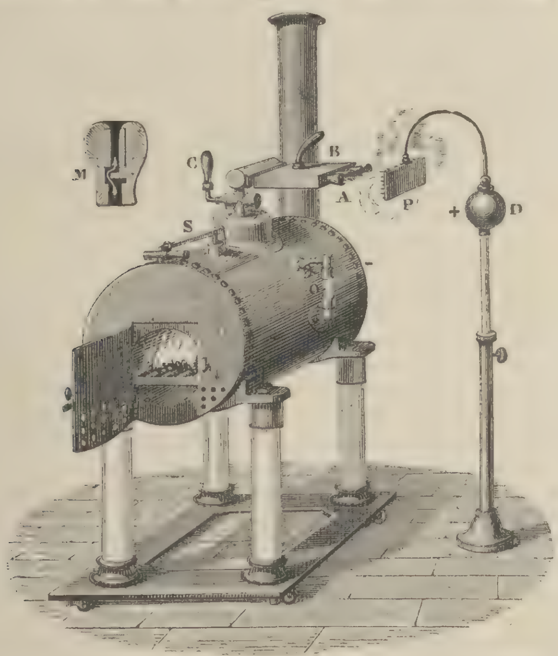


Fig. 536.

fire, and insulated on four legs. It is about 5 feet long by 2 feet in diameter, and is provided at the side with a guage O, to show the height

of the water in the boiler. C is the stopcock, which is opened when the vapour has sufficient tension. Above this is the box, B, in which are the tubes through which the vapour is disengaged. On these are fitted jets of a peculiar construction, which will be understood from the section of one of them, M, represented on a larger scale. They are lined with hard wood in a manner represented by the diagram. The box B contains cold water. Thus, the vapour, before escaping, undergoes partial condensation, and becomes charged with vesicles of water ; a necessary condition, for Faraday found that no electricity is produced when the vapour is quite dry.

The development of electricity in the machine was at first attributed to the condensation of the vapour, but Faraday found that it is solely due to the friction of the globules of water against the jet. For if the little cylinders which line the jets are changed, the kind of electricity is changed, and if ivory is substituted little or no electricity is produced. The same effect is produced if any fatty matter is introduced into the boiler. In this case the linings are of no use. It is only in case the water is pure that electricity is disengaged, and the addition of acid, or saline solutions, even in minute quantity, prevents any disengagement of electricity. If turpentine is added to the boiler, the effect is reversed, the vapour becomes negatively, and the boiler positively, electrified.

With a current of moist air, Faraday obtained effects similar to those of this apparatus, but with dry air no effect is produced.

684. **Holtz's electrical machine.**—Before the end of last century electrical machines were known in this country in which the electricity was not developed by friction, but by the continuous inductive action of a body already electrified, as the electrophorus : within the last few years such machines have been reinvented and come into use. The form represented in fig. 537 was invented by M. Holtz, of Berlin.

It consists of two circular plates of thin glass at a distance of 3 mm. from each other ; the larger one A A, which is 2 feet in diameter, is fixed by means of 4 wooden rollers, resting on glass axes and glass feet. The diameter of the second plate, B B, is 2 inches less ; it turns on a horizontal glass axis, which passes through a hole in the centre of the large fixed plate. In the plate A, on the same diameter, are two large apertures, or windows, F F′. Along the lower edge of the window F, on the posterior face of the plate, a band of paper *p* is glued, and on the anterior face a sort of tongue of thin cardboard *n*, joined to *p* by a thin strip of paper, and projecting into the window. At the upper edge of the window F′, there are corresponding parts *p*′ and *n*′. The papers *p* and *p*′ constitute the *armatures*. The two plates, the armatures, and their tongues, are carefully covered with shellac varnish, but more especially the edges of the tongues.

In front of the plate B, at the height of the armatures, are two brass *combs*, *o o*′, supported by two conductors of the same metal *c c*′. In the front end of these conductors are two pretty large brass knobs, through which pass two brass rods terminated by smaller knobs *r r*′, and provided with wooden handles K K′. These rods, besides moving with gentle

friction in the knobs, can also be turned so as to be more or less approached and inclined towards each other. The plate is turned by means

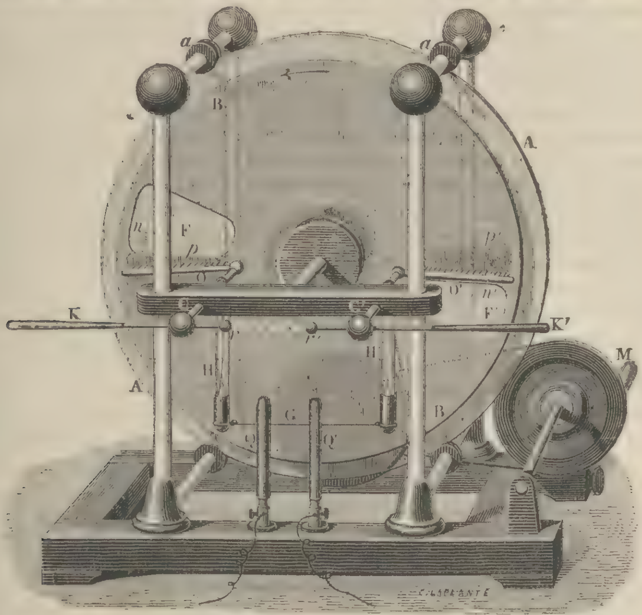


Fig. 537.

of a winch M, and a series of pulleys, which transmit its motion to the axis; the velocity which it thus receives is 12 to 15 turns in a second, and the rotation should take place in the direction indicated by the arrow, that is, towards the points of the cardboard tongues n n'.

To work the machine the armatures p p' must be first *primed*; that is, one of the armatures is positively and the other negatively electrified. This is effected by means of a sheet of ebonite, which is excited by striking it with flannel, or, better, with catskin; the two knobs r r' having been connected, the electrified ebonite is brought near one of them, p, for instance, and the plate is turned. The ebonite is charged with negative electricity, which, acting inductively on the armature p, decomposes its neutral fluid, and the negative electricity repelled is discharged by the tongue on to the moveable plate, the armature remaining charged with positive electricity. After half a turn the negative electricity of the plate coming in front of the window F′ acts in the same way on the armature p', charging it with negative electricity by taking from it a corresponding quantity of positive electricity by the tongue n'. After a few turns the two armatures being thus electrified, one positively and the other negatively, the inducing plate of ebonite is removed, and

the knobs r r' separated, as represented in the figure. On continuing to turn the plate uninterrupted, a torrent of sparks strikes across from one knob to the other.

These details being known, the following is the explanation of the action, as given by Riess. When a conductor is under the influence of an electrified body, it becomes charged with opposite electricities on its two opposite surfaces (670). This is also the case with nonconductors, with the difference, that the separation of the two electricities, which is instantaneous in the first case, takes place slowly in the second. But if between the source of electricity and a good conductor a bad conductor, such as a plate of glass, be interposed, the inductive action is modified. Supposing the source of electricity to be positive, if its action be prolonged, the good and the bad conductors are negatively electrified on the side turned towards the source, and positively on the opposite side.

If the inductive action is of short duration the influence is weak, and the electricity with which the glass plate is charged on its posterior face is negative electricity imparted by the good conductor, especially if it is provided with points. The plate B is thus electrified negatively on the two faces ; a phenomenon which Riess calls *double influence.*

That being granted, let fig. 538 represent a horizontal projection of the

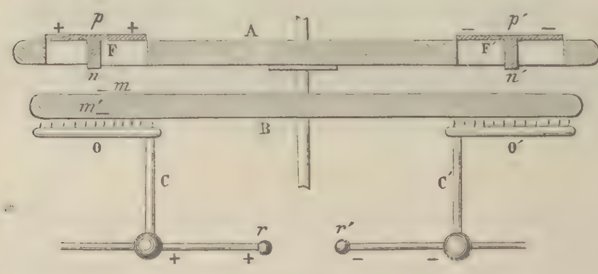


Fig. 538.

details of fig. 537, the letters having in both cases the same meaning. The two armatures p and p', having been electrified, as we have above seen, one positively and the other negatively, when two opposite elements, m and m', of the plate B, pass in front of the window F, from what has been said above, the elements m and m', in the presence of the positive armature p, both become negatively electrified ; at the same time the conductor Cr which has imparted its negative electricity to the face m of the plate B, remains positively electrified. Then, the rotation continuing, the elements m and m' both come in front of the window F F$'$ negatively charged. There the element m', adding its influence to that of the negative armature p', withdraws from the conductor C$'r'$ its positive electricity, and charges it with negative electricity. The element m, acting inductively on the armature p', withdraws positive fluid from it by induction, and thus tends to keep it in the negative state. The two elements m and m' revert to the

positive state, and passing in front of the window F the same series of phenomena is reproduced.

In Holtz's machine electricity is used in three forms, which double influence can develope. The *free* electricity of conductors is used in experiments. The electricity induced upon the external face of the moveable disc, and the electricity *communicated* to the inner face are removed by the disc, and serve to keep up the charge of the armatures. The line of the combs divides this disc in two halves, which are every minute electrified in opposite directions. Each of them is of the same kind as the conductor or armature towards which it is moving, and of opposite sign to the comb towards which the rotation carries it. The nature of the electricity is observed from the shape of the brush which escapes from it; the brushes are long and verging on the positive comb; short and like luminous points on the negative comb.

With plates of equal dimensions Holtz's machine is far more powerful than the ordinary electrical machine (678). The power is still further increased by suspending to the conductors C C′ two *condensers* H, H′ (690), which consist of two glass tubes coated with tinfoil inside and out, to within a fifth of their height. Each of them is closed by a cork, through which passes a rod, communicating at one end with the inner coating, and suspended to one of the conductors by a crook at the other end. The two external coatings are connected by a conductor G. They are, in fact, only two small Leyden jars (695), one of them, H, becoming charged with positive electricity on the inside, and negative on the outside, the other, H′, with negative electricity on the inside, and positive on the outside. Becoming charged by the intervention of the machine, and being discharged at the same rate by the knobs *r r′*, they strengthen the spark, which may attain a length of 6 or 7 inches.

The current of the machine is utilised by placing in part of the frame two brass uprights Q Q′ with binding screws in which are copper wires; then, by means of the handles K K′, the rods which support the knobs *rr′*, are inclined, so that they are in contact with the uprights. The current being then directed by the wires, a battery of six jars can be charged in a few minutes, water can be decomposed, a galvanometer deflected, and Geissler's tubes worked as with the voltaic pile.

685. **Bertsch's machine.**—This is a simpler, though at the same time less powerful, apparatus than Holtz's machine, with which it has otherwise much similarity.

It consists of an ebonite plate P P′, about 18 inches in diameter, and mounted on a glass axis (fig. 539). The inducing plate E, represented separately at the top of the figure as E′, is also of ebonite, and is placed in a groove at the base of the machine, near the plate P P′, but not in contact with it. The inducing plate E having been electrified, with negative electricity suppose, acts through the plate P on a comb *n*, withdrawing from it positive electricity, which passes to the plate and repels negative to the conductor *b*. The plate, continuing to turn, arrives charged with positive electricity in front of the second comb *m*. Hence it withdraws from the comb, and from the conductor *a*, negative electricity,

which restores it to the neutral state, and the conductor *a* remains positively charged. As the rotation of the plate is continued the conductors

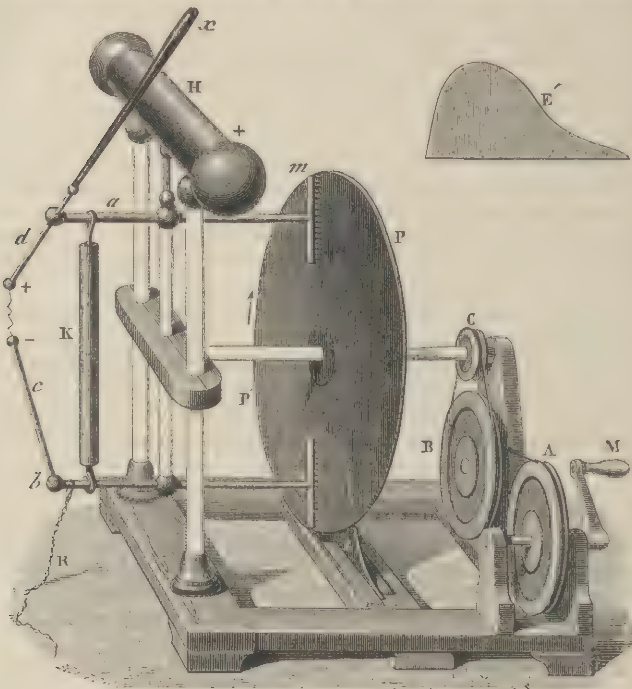


Fig. 539.

a and *b* continue to become charged with opposite electricities, and if the knobs are at a distance of 3 to 4 inches, an uninterrupted succession of sparks passes between them.

The intensity of the sparks increases when the conductor *b* is connected with the ground by means of a chain R. It is further increased by interposing a condenser K, between the conductors *a* and *b*. This consists of two stout gas tubes cemented together at the bottoms. At each end is a curved wire connected with the internal lining, which is of tinfoil. A single sheet of tinfoil coats the outside, so that they are no more than two small Leyden jars connected by their outside coatings. They become charged with contrary electricities from the conductors *a* and *b*, and being discharged at the same time as them increase the spark.

The power is increased by placing close to the sector A a second similar one, electrified in the same manner. As the inducing power increases, the tension also increases. With a machine thus arranged, a glass plate $\frac{1}{8}$ to $\frac{1}{6}$ of an inch may be perforated, and a strong battery

rapidly charged. The inducing power of the sectors quickly decreases, and they must be excited afresh.

Both Holtz's and Bertsch's machines are very much affected by the moisture of the air; but M. Ruhmkorff has found that, spreading on the table a few drops of petroleum, the vapours which condense on the machine protect it against the moisture of the atmosphere.

These machines are small in compass, and not very expensive, and require less force for working them than frictional machines. When the armatures are electrified, more resistance is experienced in turning the plate than if they are not electrified; in the former case part of the mechanical force exerted by the arm of the operator is transformed into electricity.

686. **Carre's dielectrical machine.**—This is a combination of the old form of machine with that of Holtz.

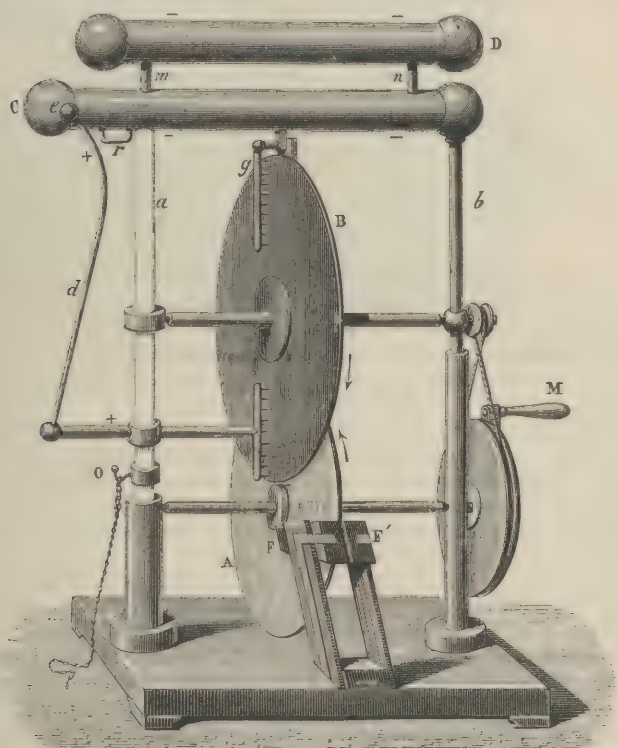


Fig. 540.

It consists of two plates turning in opposite directions (fig. 540), one A of glass and the other of ebonite. They overlap each other to about ⅔ to

$\frac{3}{4}$ of their radii. The lower one is slowly turned by means of a handle M, while the upper one is rapidly rotated by an endless cord, which passes from the large over the small wheel.

The plate A, after having been electrified positively between two rubbers F F′, acts inductively through the plate B on a comb *i*, withdrawing from it negative electricity, which then passes to the plate B, the conductor *d e* remaining positively electrified ; but as the plate B turns very quickly the negative electricity, as it collects on its surface, acts inductively on a second comb *g*, which it charges with negative electricity, reverting itself to the neutral state, while the two conductors C and D, which are connected with the comb *g*, become charged with negative electricity.

These conductors, connected as they are by two ties *m* and *n*, rest on two columns, the one *a* of glass, and the other *b* of ebonite. A chain in connexion with the ground is suspended from a hook O which can be raised at pleasure, and put in connexion with the comb *i*. The rubbers F F′, moreover, are in connexion with the ground by means of two bands of tin foil along the supports.

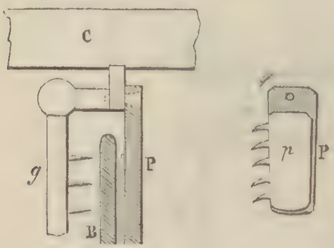


Fig. 541.

Lastly, at *p* (fig. 541) is a sector of varnished paper cut in the form of a comb, and fastened to an insulating segment P of the same shape, which is used as support. From the teeth of the sector *p* positive electricity flows on the plate B as it moves, and by induction this sector *p* yields to the comb *g* a surcharge of negative electricity. The rod *d* and the knob *e* may be withdrawn at will from the conductor C (fig. 540), so that sparks of different lengths may be taken. At *r* is a hook to which can be attached the Leyden jars which are to be charged.

Owing to the direct action, and when the inducing plate is at the maximum charge, Carre's machine is not very much affected by moisture, and it yields a larger supply of electricity. With plates whose dimensions are respectively 38 and 49 centimètres, it gives sparks of 15 to 18 centimètres, and more when a condenser is added, as in Holtz's and Bertsch's machines.

EXPERIMENTS WITH THE ELECTRICAL MACHINE.

687. **Spark.**—One of the most curious phenomena observed with the electrical machine is the spark drawn from the conductor when a finger is presented to it. The positive electricity of the conductor, acting inductively on the neutral fluid of the body, decomposes it, repelling the positive and attracting the negative fluid. When the tension of the opposed electricities is sufficiently great to overcome the resistance of the air, they recombine with a smart crack and a spark. The spark is instantaneous, and is accompanied by a sharp prickly sensation, more

especially with a powerful machine. Its shape varies. When it strikes at a short distance, it is rectilinear, as seen in fig. 542. Beyond two or three inches in length, the spark become irregular, and has the form of

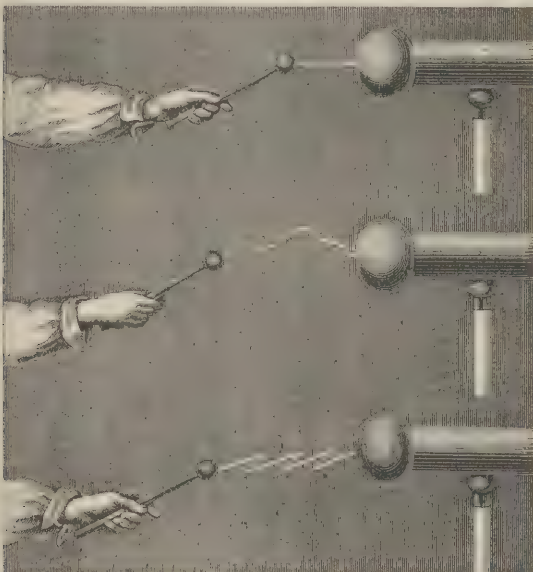


Fig. 542.

Fig. 543

Fig. 544.

a sinuous curve with branches (fig. 543). If the discharge is very powerful, the spark takes a zigzag shape (fig. 544). These two latter appearances are seen in the lightning discharge.

A spark may be taken from the human body by the aid of the *insulating stool*, which is simply a low stool with stout glass legs. The person standing on this stool touches the prime conductor, and as the human body is a conductor, the electrical fluid is distributed over its surface as over an ordinary insulated metallic conductor. The hair diverges in consequence of repulsion, a peculiar sensation is felt on the face, and if another person, standing on the ground, presents his hand to any part of the body, a smart crack with a pricking sensation is produced.

A person standing on an insulated stool may be positively electrified by being struck with a catskin. If the person holding the catskin stands on an insulated stool, the striker becomes positively, and the person struck negatively, electrified.

688. **Electrical chimes.**—The *electrical chimes* is a piece of apparatus consisting of three bells suspended to a horizontal metal rod (fig. 545). Two of them, A and B, are in metallic connection with the conductor; the middle bell hangs by a silk thread, and is thus insulated from the conductor, but is connected with the ground by means of

a chain. Between the bells are small copper balls suspended by silk threads. When the machine is worked, the bells A and B, being positively electrified, attract the copper balls, and after contact repel them. Being now positively electrified, they are in turn attracted by the middle bell C, which is charged with negative electricity by induction from A to B. After contact they are again repelled, and this process is repeated as long as the machine is in action.

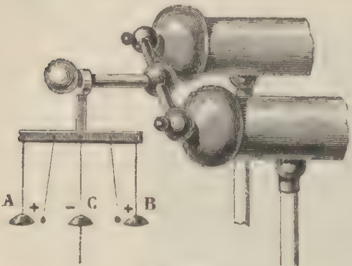


Fig. 545.

Fig. 546 represents an apparatus originally devised by Volta for the purpose of illustrating what he supposed to be the motion of hail between two clouds oppositely electrified. It consists of a tubulated glass shade, with a metal base, on which are

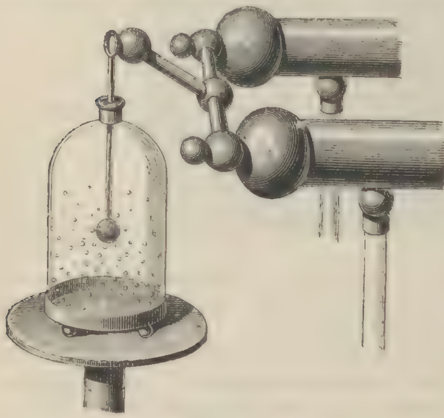


Fig. 546.

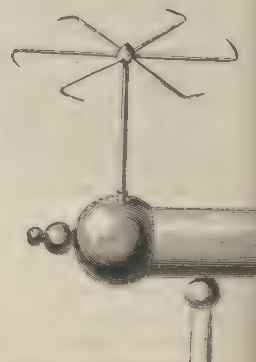


Fig. 547.

some pithballs. The tubulure has a metal cap, through which passes a brass rod, provided with a metallic disc or sphere at the lower end, and at the upper with a knob, which touches the prime conductor.

When the machine is worked, the sphere, becoming positively electrified, attracts the light pithballs, which are then immediately repelled, and, having lost their charge of positive electricity, are again attracted, again repelled, and so on, as long as the machine continues to be worked. An amusing modification of this experiment is frequently made by placing between the two plates small pith figures, somewhat loaded at the base. When the machine is worked, the figures execute a regular dance.

689. **Electrical whirl or vane.**—The electrical *whirl* or *vane* consists of 5 or 6 wires, terminating in points, all bent in the same direction, and fixed in a central cap, which rotates on a pivot (fig. 547). When the

apparatus is placed on the conductor, and the machine worked, the whirl begins to revolve in a direction opposite that of the points. This motion is not analogous to that of the hydraulic tourniquet (201). It is not caused by a flow of material fluid, but is owing to a repulsion between the electricity of the points and that which they impart to the adjacent air by conduction. The electricity being accumulated on the points in a high state of tension, passes into the air, and imparting thus a charge of electricity, repels this electricity, while it is itself repelled. That this is the case, is evident from the fact that on approaching the hand to the whirl while in motion, a slight draught is felt, due to the movement of the electrified air, while in vacuo the apparatus does not act at all. This draught or wind is known as the electrical *aura*.

When the electricity thus escapes by a point, the electrified air is repelled so strongly as not only to be perceptible to the hand, but also to engender a current strong enough to blow out a candle. Fig. 548 shows

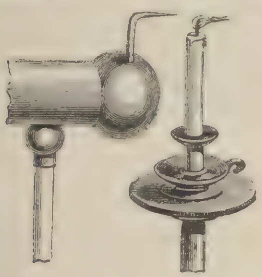


Fig. 548.

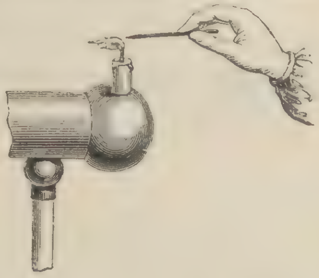


Fig. 549.

this experiment. The same effect is produced by placing a taper on the conductor, and bringing near it a pointed wire held in the hand (fig. 549). The current arises, in this case, from the contrary fluid, which escapes by the point under the influence of the machine.

The *electrical orrery* and the *electrical inclined plane* are analogous to these pieces of apparatus.

CHAPTER IV.

CONDENSATION OF ELECTRICITY.

690. **Condensers, Theory of condensers.**—A *condenser* is an apparatus for condensing a large quantity of electricity on a comparatively small surface. The form may vary considerably, but in all cases consists essentially of two insulated conductors, separated by a nonconductor, and the working depends on the action of induction.

Epinus's condenser consists of two circular brass plates, A and B

(fig. 550), with a sheet of glass C, between them. The plates, each provided with a pith ball pendulum, are mounted on insulating glass legs, and can

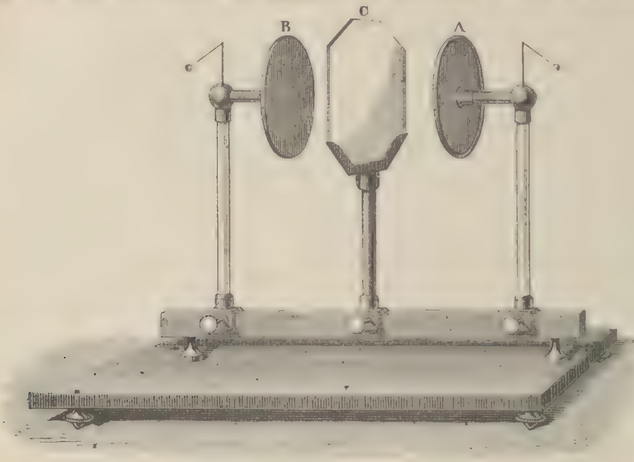


Fig. 550.

be moved along a support, and fixed in any position. When electricity is to be accumulated, the plates are placed in contact with the glass, and then one of them, B for instance, is connected with the electrical machine, and the other placed in connection with the ground, as shown in fig. 551.

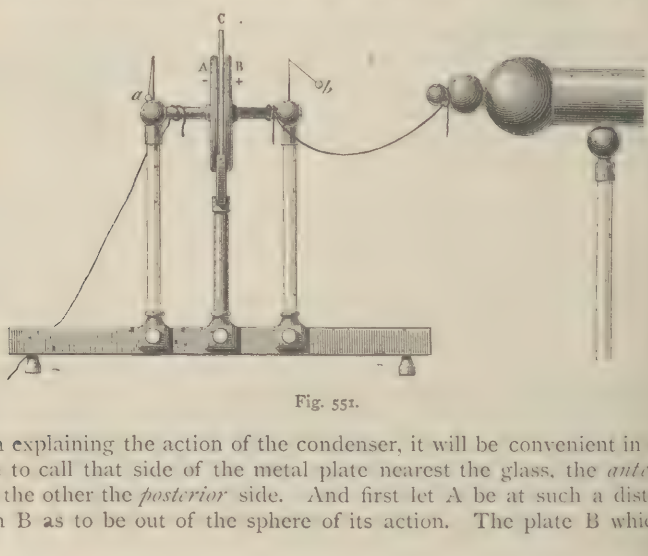


Fig. 551.

In explaining the action of the condenser, it will be convenient in each case to call that side of the metal plate nearest the glass, the *anterior*, and the other the *posterior* side. And first let A be at such a distance from B as to be out of the sphere of its action. The plate B which is

then connected with the conductor of the electrical machine, takes its maximum charge, which is distributed equally on its two faces, and the pendulum diverges widely. If the connection with the machine be interrupted, nothing would be changed; but if the plate A be slowly approached, its neutral fluid being decomposed by the influence of B, the negative is accumulated on its anterior face *n* (fig. 552), and the positive passes into the ground. But as the negative electricity of the plate A reacts in its turn on the positive of the plate B, the latter fluid ceases to be equally distributed on both faces, and is accumulated on its anterior face *m*. The posterior face, *p*, having thus lost a portion of its electricity, its tension has diminished, and is no longer equal to that of the machine, and the pendulum, *b*, diverges less widely. Hence B can receive a fresh quantity from the machine, which, acting as just described, decomposes by induction a second quantity of neutral fluid on the plate A. There is then a new accumulation of negative fluid on the face *n*, and consequently of positive fluid on *m*. But each time that the machine gives off electricity to the plate, only a part of this passes to the face *m*, the other remaining on the face *p*; the tension here, therefore, continues to increase until it equals that of the machine. From this moment equilibrium is established, and a limit to the charge attained, which cannot be exceeded. The quantity of electricity accumulated now on the two faces *m* and *n* is very considerable, and yet the pendulum diverges just as much as it did when A was absent and no more; in fact, the tension at *p* is just what it was then, namely, that of the machine.

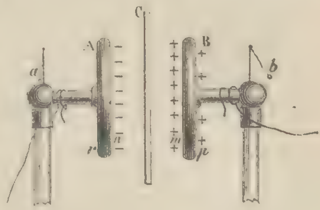


Fig. 552.

When the condenser is charged, that is, when the opposite electricities are accumulated on the anterior faces, connection with the ground is broken by raising the wires. The plate A is charged with negative electricity, but simply on its anterior face (fig. 552), the other side being neutral. The plate B, on the contrary, is electrified on both sides, but unequally; the accumulation is only on its anterior face, while on the posterior, *p*, the tension is simply equal to that of the machine at the moment the connections are interrupted. In fact, the pendulum *b* diverges and *a* remains vertical. But if the two plates are removed the two pendulums diverge (fig. 550), which is owing to the circumstance that as the plates no longer act on each other, the positive fluid is equally distributed on the two faces of the plate B, and the negative on those of the plate A.

691. **Slow discharge and instantaneous discharge.**—While the plates A and B are in contact with the glass (fig. 551), and the connections interrupted, the condenser may be discharged, that is, restored to the neutral state, in two ways; either by a slow or by an instantaneous discharge. To discharge it slowly the plate B, that is, the one containing an excess of electricity, is touched with the finger; a spark passes, all

the electricity on p passes into the ground, the pendulum b falls, but a diverges. For B having lost part of its electricity, only retains on the face m that held by the inductive influence of the negative on A. But the quantity thus retained at B is less than that on A; this has free electricity which makes the pendulum a diverge, and, if it now be touched, a spark passes, the pendulum a sinks while b rises, and so on by continuing to touch alternately the two plates. The discharge only takes place slowly; in very dry air it may require several hours. If the plate A were touched first, no electricity would be removed, for all it has is retained by that of the plate B. To remove the total quantity of electricity by the method of alternate contacts, an infinite number of such contacts would theoretically be required, as will be seen from the following calculation:

Let the total quantity of positive electricity on B be taken $= 1$; by induction it retains on A a quantity less than its own of negative electricity; let this quantity be called m; m being a fraction in all cases less than unity, but which varies with the distance of the plates and the nature of the dielectric. Now the m of negative electricity on A reacting in turn on the positive on B, retains there $m \times m = m^2$ of positive electricity, and therefore the free electricity on B, that which makes the pendulum b diverge, is $1 - m^2$, and if B be touched this quantity is removed. The m of negative on A now retains, on B, m^2 of positive; this binds in turn m times its own quantity, that is, m^3 of negative on A, and the free negative electricity which now makes the pendulum a diverge is represented by $m - m^3 = m(1 - m^2)$. If A be now touched this quantity is removed, the pendulum a sinks and b rises, for B has now an excess of free electricity, which it is readily seen is represented by $m^2(1 - m^2)$. By pursuing this reasoning it will be seen that the following expresses the quantities removed and left after each successive contact:—

Positive		Negative	
	1	m	
$1 - m^2$;	m^2	m^3;	$m(1 - m^2)$
$(1 - m^2)m^2$;	m^4	m^5;	$m^3(1 - m^2)$
$(1 - m^2)m^4$;	m^6	m^7;	$m^5(1 - m^2)$
$(1 - m^2)m^{n-2}$;	m^n	m^{n+1};	$m^{n-1}(1 - m^2)$

An instantaneous discharge may be effected by means of the *discharging rod* (fig. 553). This consists of two bent brass wires, terminating on knobs, and joined by a hinge. When provided with glass handles, as in fig. 553, it forms a *glass discharging rod.* In using this apparatus one of the knobs is pressed against one plate of the condenser, and the other knob brought near the other. At a certain distance a spark strikes from the plate to the knob, caused by the sudden recomposition of the two opposite electricities.

When the condenser is discharged by the discharger no sensation is experienced, even though the latter be held in the hand; of the two conductors, the electric fluid always chooses the better, and hence the discharge is effected through the metal, and not through the body. But if

while one hand is in contact with one plate, the other touches the second, the discharge takes place through the breast and arms, and a considerable shock is felt; and the larger the surface of the condenser, and the greater the electric tension, the more violent is the shock.

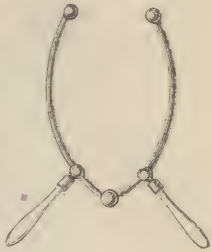


Fig. 553.

692. **Calculation of the condensing force.**—The condensing force is the relation between the whole charge, which the collecting plate can take while under the influence of the second plate, to that which it would take if alone; in other words, it is the relation of the total quantity of electricity on the collecting plate to that which remains free; for it is assumed that the quantity of free electricity on the collecting plate is the same as that which it would take if it were alone.

To calculate the condensing force, let us, as before, express the total quantity of positive electricity which the collecting plate B can take while under the influence of the condensing plate, by 1, then m is the whole quantity of negative electricity on the second plate. But, as we have just seen, the quantity of free electricity on B is $1-m^2$. Hence $\frac{1}{1-m^2}$ is the fraction which expresses the condensing force.

The value of m is determined experimentally by means of the proof plane and the torsion balance. Thus, if m were 0·99 the quantity of electricity which could be accumulated on the collecting plate B, under the influence of A, would be 50 times as much as the quantity it could receive if alone; while if m were 0·75 the quantity would be 2·28 times as great.

693. **Limit of the charge of condensers.**—The quantity of electricity which can be accumulated on each plate is, *cæteris paribus*, proportional to the tension of the electricity on the conductor, and to the surface of the plates: it decreases as the insulating plate is thicker, and it differs with the specific inductive capacity of the substance. Two causes limit the quantity of electricity which can be accumulated. First, that the electric tension of the collecting plates gradually increases, and ultimately equals that of the machine, which cannot, therefore, impart any free electricity. The second cause is the imperfect resistance which the insulating plate offers to the recombination of the two opposite electricities; for when the force which impels the two fluids to recombine exceeds the resistance offered by the insulating plate, it is perforated, and the contrary fluids unite.

694. **Fulminating pane.**—This is a simple form of the condenser, and is more suitable for giving strong shocks and sparks. It consists of a glass plate fixed in a wooden frame (fig. 554); on each side of the glass pieces of tin foil are fastened opposite each other, leaving a space free between the edge and the frame. It is well to cover this part of the glass with an insulating layer of shellac varnish. One of the sheets of tin foil is connected with a ring on the frame by a strip of tin foil, so that it can

be put in communication with the ground by means of a chain. To charge the pane the insulated side is connected with the machine. As the other

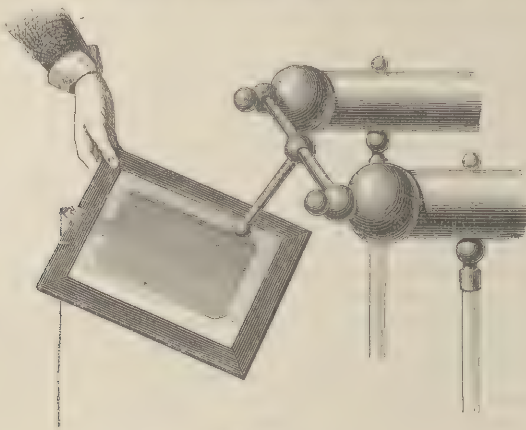


Fig. 554.

side communicates with the ground, the two coatings play exactly the part of a condenser. On both plates there are accumulated large quantities of contrary electricities.

The pane may be discharged by simply pressing the knob of the discharger against the lower surface, while the other knob is brought near the upper coating. A spark ensues, due to the recomposition of the two electricities ; but the operator experiences no sensation, for the discharge takes place through the wire. But if the connection between the two coatings be made by touching them with the hands, a violent shock is felt in the hands and breast, for the combination then takes place through the body.

695. **Leyden jar.**—The *Leyden jar*, so named from the town Leyden, where it was invented, is nothing more than a modified condenser or fulminating plane rolled up. Fig. 555 represents a Leyden jar of the usual French shape in the process of being charged. It consists of a glass bottle of any convenient size, the interior of which is either coated with tin foil or filled with thin leaves of copper, or with gold leaf. Up to a certain distance from the neck the outside is coated with tin foil. The neck is provided with a cork, through which passes a brass rod, which terminates at one end in a knob, and communicates with the metal in the interior. The metallic coatings are called respectively the *internal* and *external coatings*. Like the condenser, the jar is charged by connecting one of the coatings with the ground, and the other with the source of electricity. When it is held in the hand by the external coating, and the knob presented to the positive conductor of the machine, positive electricity is accumulated on the inner, and negative electricity on the outer coating. The reverse is the case if the jar is held by the knob, and the external

coating presented to the machine. The positive discharge acting inductively across the dielectric glass, decomposes the electricity of the outer

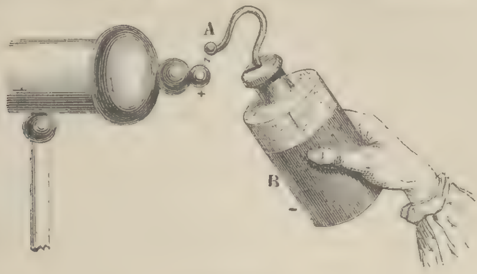


Fig. 555.

coating, attracting the negative, and repelling the positive, which being free escapes by the hand to the ground. Thus it will be seen that the theory of the jar is identical with that of the condenser, and all that has been said of this applies to the jar, substituting the two coatings for the two plates, A and B, of fig. 551.

Like the condenser, the Leyden jar may be discharged either slowly or instantaneously. For the latter it is held in the hand by the outside coating (fig. 556), and the two coatings are then connected by means of the simple

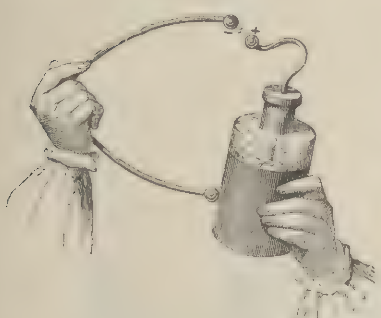


Fig. 556.

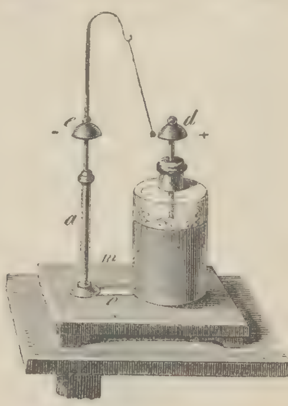


Fig. 557.

discharger. Care must be taken to touch *first* the external coating with the discharger, otherwise a smart shock will be felt. To discharge it slowly the jar is placed on an insulated plate, and first the internal and then the external coating touched, either with the hand or with a metallic conductor. A slight spark is seen at each discharge.

Fig. 557 represents a very pretty experiment for illustrating the slow discharge. The rod terminates in a small bell, *d*, and the outside coating is

connected with an upright metallic support, on which is a similar bell, *c*. Between the two bells a light copper ball is suspended by a silk thread. The jar is then charged in the usual manner and placed on the support *m*. The internal coating contains a quantity of free electricity ; the pendulum is attracted and immediately repelled, striking against the second bell, to which it imparts its free electricity. Being now neutralised, it is again attracted by the first bell, and so on for some time, especially if the air be dry, and the jar pretty large.

696. **Leyden jar with moveable coatings.**—This apparatus (fig. 558) is used to demonstrate that in the Leyden jar, the opposite electricities are not distributed on the coatings merely, but reside principally on the opposite sides of the glass. It consists of a somewhat conical glass vessel, B, with moveable coatings of zinc or tin, C and D. These separate pieces placed one in the other, as shown in figure A, form a complete Leyden jar. After having charged the jar, it is placed on a cake of resin ; the internal coating is first removed by the hand, or better a glass rod, and then the glass vessel. The coatings are found to contain very little electricity, and if they are placed on the table they are reduced to the neutral state. Nevertheless, when the jar is put together again, as represented in the figure at A, a shock may be taken from it almost as strong as if the coatings had not been removed. It is therefore concluded that the coatings merely play the part of conductors, distributing the electricity over the surface of the glass, which thus becomes polarised, and retains this state even when placed on the table, owing to its want of conductivity.

The experiment may be conveniently made by forming a Leyden jar, of which the inside and outside coatings are of mercury, charging it ; then, having mixed the two coatings, the apparatus is put together again, upon which a discharge may be once more taken.

697. **Lichtenberg's figures.**—This experiment well illustrates the opposite electrical conditions of the two coatings of a Leyden jar. Holding a

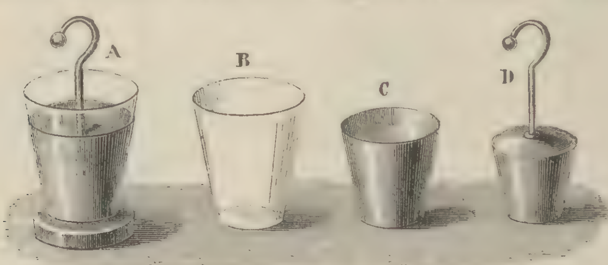


Fig. 558

jar charged with positive electricity by the hand, a series of lines are drawn with the knob on a cake of resin or vulcanite ; then having placed the jar on an insulator, it is held by the knob, and another series traced by means of the outer coating. If now an intimate mixture of red lead and flour of

sulphur be projected on the cake, the sulphur will attach itself to the positive lines, and the red lead to the negative lines; the reason being that in mixing the powders the sulphur has become negatively electrified, and the red lead positively. The sulphur will arrange itself in tufts with numerous diverging branches, while the red lead will take the form of small circular spots, indicating a difference in the distribution of the two electricities on the surface of the resin.

698. **Penetration of the charge. Residual charge.**—Not only do the electricities adhere to the two surfaces of the insulating medium which separates them, but they penetrate to a certain extent into the interior, as is shown by the following experiments: A condenser is formed of a plate of shellac, and moveable metallic plates. It is then charged, retained in that state for some time, and afterwards discharged. On removing the metallic coatings and examining both surfaces of the insulator, they show no signs of electricity. After some time, however, each face exhibits the presence of some electricity of the same kind as that of the plate with which it was in contact while the apparatus was charged. This can be explained by assuming that the electricity had slowly penetrated from the exterior to the interior during the first phase of the experiment, and had returned to the surface during the second.

A phenomenon frequently observed in Leyden jars is of the same nature. When a jar has been discharged and allowed to stand a short time, it exhibits a second charge, which is called the *electric residue*. The jar may be again discharged, and a second residue will be left, feebler than the first, and so on, for three or four times. Indeed with a delicate electroscope a long succession of such residues may be demonstrated. Time is required for the penetration of the electricities into the mass; and hence the residue is greater the longer the jar has remained charged. The magnitude of the residue further depends on the intensity of the charge, and also on the degree of contact of the metallic plates with the insulator. It varies with the nature of the substance, but there is no residue with either liquids or gaseous insulators. Faraday found that with paraffine the residue was greatest, then with shellac, while with glass and sulphur it was least of all. Kohlrausch has found that the residue is nearly proportional to the thickness of the insulator.

699. **Electric batteries.**—The charge which a Leyden jar can take depends on the extent of the coated surface, and for small thicknesses is inversely proportional to the thickness of the insulator. Hence, the larger and thinner the jar the more powerful the charge. But very large jars are expensive, and liable to break; and when too thin, the accumulated electricities are apt to discharge themselves through the glass, especially if it is not quite homogeneous. Leyden jars have usually from $\frac{1}{2}$ to 3 square feet of coated surface. For more powerful charges electric batteries are used.

An *electric battery* consists of a series of Leyden jars, whose internal and external coatings are respectively connected with each other (fig. 559). They are usually placed in a wooden box lined on the bottom with tin foil. This lining is connected with two metallic handles in the sides of the box.

The internal coatings are connected with each other by metallic rods, and the battery is charged by placing the internal coatings in connection with the prime conductor, while the external coatings are connected with the ground by means of a chain fixed to the handles. A quadrant electrometer

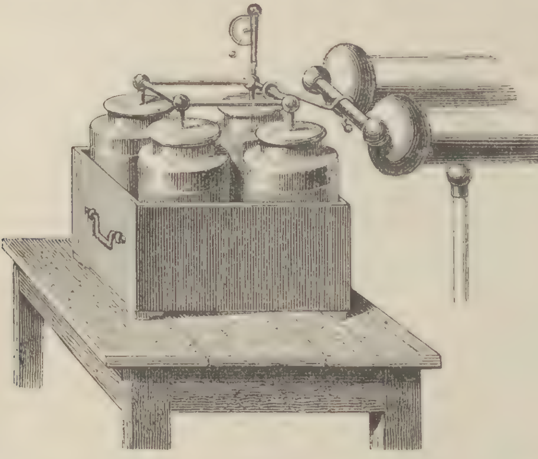


Fig. 559.

fixed to the jar serves to indicate the charge of the battery. Although there is a large quantity of electricity accumulated in the apparatus the divergence is not great, for it is simply due to the free electricity on the internal coating. The number of jars is usually four, six, or nine. The larger and more numerous they are, the longer is the time required to charge the battery, but the effects are so much the more powerful.

When a battery is to be discharged, the coatings are connected by means of the discharging rod, the outside coating being touched first. Great care is required, for with large batteries serious accidents may occur, resulting even in death.

700. **The universal discharger.**—This is an almost indispensable apparatus in experiments with the electric battery. On a wooden stand (fig. 560) are two glass legs, each provided with universal joints, in which moveable brass rods are fitted. Between these legs is a small ivory table, on which is placed the object under experiment. The two metal knobs being directed towards the objects, one of them is connected with the external coating of the battery, and the moment communication is made between the other and the internal coating by means of the glass discharging rod, a violent shock passes through the object on the table.

701. **Charging by cascade.**—A series of Leyden jars are placed each separately on insulating supports. The knob of the first is in connection with the prime conductor of the machine, and its outer coating joined to the knob of the second, the outer coating of the second to the knob of the third, and so on; the outer coating of the last communicating with the

ground. The inner coating of the first receives a charge of positive electricity from the machine, and the corresponding positive electricity set

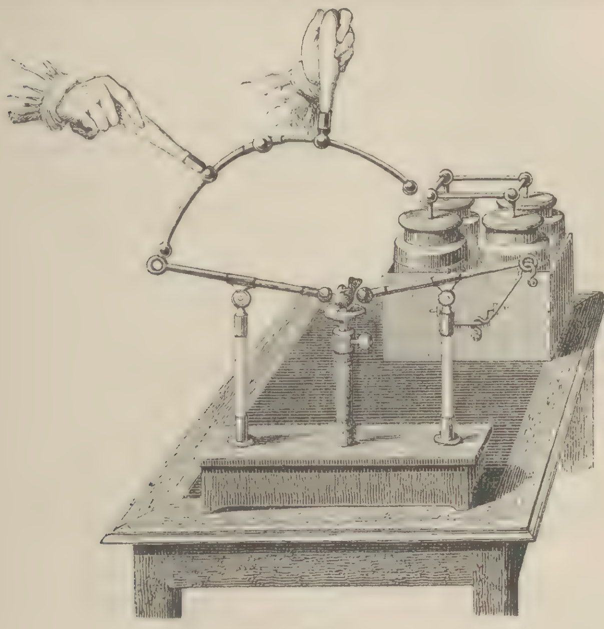


Fig. 560.

free by induction on its outer coating, instead of passing to the ground, gives a positive charge to the inner coating of the second, which, acting in like manner, develops a charge in the third jar, and so on, to the last, where the positive electricity developed by induction on the outer coating passes to the ground. The jars may be discharged either singly, by connecting the inner and outer coatings of each jar, or simultaneously by connecting the inner coating of the first with the outer of the last. In this way the quantity of electricity necessary to charge one jar is available for charging a series of jars.

For from the preceding explanation it is clear, that with a series of similar Leyden jars charged by cascade, if we call the charge of positive electricity which the inside of the first jar receives 1, it will develop by induction on the outside a quantity $m(m < 1)$ of negative electricity, and the same quantity m of positive electricity which will pass into the inside of the second jar ; this in turn will develop $m \times m = m^2$ of negative electricity on the outside of that jar, and the same quantity m^2 of positive electricity will pass into the inside of the third jar, and so forth. Thus it will be seen that the quantities of positive electricity developed in a series of n similar jars by the unit charge of positive electricity will be

$$1 + m + m^2 + m^3 + \quad . \quad . \quad . \quad . \quad m^{n-1} = \frac{1 - m^n}{1 - m}$$

and of negative electricity on the corresponding outsides of

$$m + m^2 + m^3 + m^4 + \quad . \quad . \quad . \quad . \quad m^n = \frac{m(1 - m^n)}{1 - m}.$$

Thus, if there be six jars and $m = 0 \cdot 9$, the quantity of positive electricity developed by the unit charge is 4·69.

If the external coatings of a charged and uncharged jar are placed in connection, and if the inner coatings are now connected, after separating them they are both found to be charged in the same direction. In this process a current has been produced between the outside coatings and one between the inner ones, to which Dove has given the name *charge current*, and which has all the properties of the ordinary discharge current.

702. **Measurement of the charge of a battery. Lane's electrometer.**—When the outer and inner coatings of a charged Leyden jar are gradually brought near each other, at a certain distance a spontaneous discharge ensues. This distance is called the *striking distance*. It is inversely proportional to the pressure of the air and directly proportional to the electric density of that point of the inner coating at which the discharge takes place. As the density of any point of the inner coating, other things remaining the same, is proportional to the entire charge, the striking distance is proportional to the quantity of electricity in a jar. The measurement of the charge of a battery, however, by means of the striking distance, can only take place when the charge disappears.

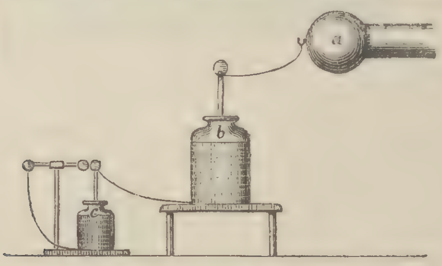


Fig. 561.

By means of Lane's electrometer, which depends on an application of this principle, the charge of a jar or battery may be measured. This apparatus, c (fig. 561), consists of an ordinary Leyden jar, near which there is a vertical metallic support. At the upper end is a brass rod, with a knob at one end, which can be placed in metallic connection with the outside of the jar ; the rod being moveable, the knob can be kept at a measured distance from the knob of the inner coating. Fig. 561 represents the operation of measuring the charge of a jar by means of this apparatus. The jar b, whose charge is to be measured, is placed on an insulated stool with its outer coating in metallic connection with the inner coating of Lane's jar c, the outer coating of which is in connection with

the ground, or still better with a system of gas or water pipes; a is the conductor of the machine. When the machine is worked positive electricity passes into the jar b; a proportionate quantity of positive electricity is repelled from its outer coating, passes into the inner coating of the electrometer, and there produces a charge. When this has reached a certain limit, it discharges itself between the two knobs, and so often as such a discharge takes place the same quantity of positive electricity will have passed from the machine into the battery; and hence its charge is proportional to the number of discharges of the electrometer.

Harris's unit jar (fig. 562) is an application of the same principle, and is very convenient for measuring quantities of electricity. It consists of a small Leyden phial 4 inches in length, and $\frac{3}{4}$ of an inch in diameter, coated to about an inch from the end, so as to expose about 6 inches of coated surface. It is fixed horizontally on a long insulator, and the charging rod connected at P with the conductor of the machine, while the outer coating is conected with the jar or battery by the rod *tp*. When the accumulation of electricity in the interior has reached a certain height depending on the distance of the two balls m and n, a discharge ensues, and marks a certain quantity of electricity received as a charge by the battery in terms of the small jar.

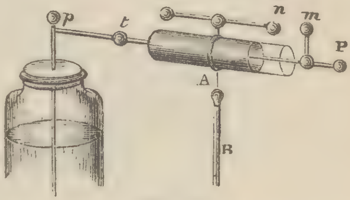


Fig. 562

703. **Laws of electric charge.**—Harris, by means of experiments with the unit jar suitably modified, and Riess, by analogous arangements, have found, by independent researches, that for small distances the striking distance is directly proportional to the quantity of electricity, and inversely proportional to the extent of coated surface; in other words, it is proportional to the electric density. Thus, taking the surface of one jar as unity, if a battery of six Leyden jars charged by 100 turns of the machine has a striking distance of 9 millimeters, a battery of four similar jars charged by 120 turns will have the striking distance of 16·2 millimeters. For

$$\frac{100}{6} : 9 = \frac{120}{4} : x$$
$$x = 16{\cdot}2.$$

The charge also depends on the nature of the glass, or other dielectric, of which the jar is made; and further, is stated by Wheatstone to be inversely proportional to the square of the thickness of the dielectric. Riess has also found that when a battery or jar is discharged in the striking distance, a charge still remains, for when the coatings are brought nearer a similar discharge may be taken, and so on. The amount of this residual charge when the discharge takes place at the greatest striking distance is *always in the same proportion to the entire charge.* In Riess's experiments, 0·846 or $\frac{11}{13}$ of the total charge disappear, and only $\frac{2}{13}$ remain.

704. **Volta's condensing electroscope.**—The condensing electroscope invented by Volta is a modification of the ordinary gold leaf electroscope (676). The rod to which the gold leaves are affixed terminates in a disc instead of in a knob, and there is another disc of the same size provided with an insulating glass handle. The discs are covered with a layer of insulating shellac varnish (fig. 563).

Fig. 563.

Fig. 564.

To render very small quantities of electricity perceptible by this apparatus, one of the plates, which thus becomes the *collecting plate*, is touched with the body under examination. The other plate, the *condensing plate*, is connected with the ground by touching it with the finger. The electricity of the body, being diffused over the collecting plate, acts inductively through the varnish on the neutral fluid of the other plate, attracting the opposite electricity, but repelling that of like kind. The two electricities thus become accumulated on the two plates just as in Epinus' condenser, but there is no divergence of the leaves, for the opposite electricities counteract each other. The finger is now removed, and then the source of electricity, and still there is no divergence; but if the upper plate be raised (fig. 564) the neutralisation ceases, and the electricity being free to move diffuses itself over the rod and the leaves, which then diverge widely. The delicacy of the apparatus is increased by adapting to the foot of the apparatus two metallic rods, terminating in knobs, for these knobs being excited by induction from the gold leaves react upon them.

A still further degree of delicacy is attained by replacing the rods by

two Bohnenberger's dry piles, one of which presents its positive and the other its negative pole. Instead of two gold leaves there is only one; the least trace of electricity causes it to oscillate either to one side or to the other, and at the same time shows the kind of electricity.

705. **Thomson's electrometer.**—Sir William Thomson has devised a new and delicate form of electrometer, by which quantitative measurements of the amount of electrical charge may be made. The principle of this instrument may be understood from the following description of a model of it constructed for lecture purposes by Messrs. Elliott, by whom the drawing has been kindly furnished.

A light flat aluminium needle B, balanced by a counterpoise, is suspended by a platinum wire from a support connected with the inner coating of a Leyden jar, A. CC are two half rings of metal, resting on glass supports, but connected by means of wires with the two knobs DD. When the needle B is at rest it is directly over the division between the two rings. Supposing the needle B not charged with electricity, then if one knob, D, the right hand one, for instance, be connected with any body charged with electricity, while the other is connected with the earth, the needle will turn slightly towards C, and this whether the electricity of the D in question is positive or negative. But if the Leyden jar be charged, say with negative electricity, the needle will receive an equal charge, or, as is now generally expressed, will be *at the same potential.* It will now be more strongly attracted than before if the charge of D be positive, and would be more powerfully repelled if the charge of D were negative. If D loses its electricity, and is therefore in the same condition as the earth, B returns to its original position between the two rings. One object of connecting the needle with a Leyden jar is to provide a considerable supply of electricity for the needle, so that the small leakage which occurs may not affect one test, or even a series of tests. The deflections will be greater and the instrument more powerful the higher the jar is charged, but the indications will only be constant so long as the jar is charged to the same degree. The apparatus is placed under a bell jar, and the vessel E contains sulphuric acid, by which the air in the interior is kept dry. In the instrument a little mirror is hung above the needle, as in the reflecting galvanometers (738), and the deflections noted by a spot of light reflected from a lamp.

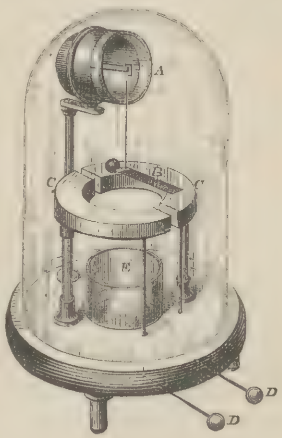


Fig. 565.

THE ELECTRIC DISCHARGE.

706. **Effects of the electric discharge.**—The recombination of the two electricities which constitutes the electrical discharge may be either continuous or sudden; *continuous*, or of the nature of a current, as when the two conductors of a cylinder machine are joined by a chain or a wire; and *sudden*, as when the opposite electricities accumulate on the surface of two adjacent conductors, till their mutual attraction is strong enough to overcome the intervening resistances, whatever they may be. But the difference between a sudden and a continuous discharge is one of degree, and not of kind, for there is no such thing as an absolute non-conductor, and the very best conductors, the metals, offer an appreciable resistance to the passage of electricity. Still, the difference at the two extremes of the scale is sufficiently great to give rise to a wide range of phenomena.

The phenomena of the discharge are usually divided into the *physiological*, *luminous*, *mechanical*, *magnetical*, and *chemical* effects.

707. **Physiological effects.**—The physiological effects are those produced on living beings, or on those recently deprived of life. In the first case they consist of a violent excitement which the electric fluid exerts on the sensibility and contractibility of the organic tissues through which it passes; and in the latter, of violent muscular convulsions which resemble a return to life.

The shock from the electrical machine has been already noticed (695). The shock taken from a charged Leyden jar by grasping the external coating with one hand, and touching the inner with the other, is much more violent, and has a peculiar character. With a small jar the shock is felt in the elbow; with a jar of about a quart capacity it is felt across the chest, and with jars of still larger dimensions in the stomach.

A shock may be given to a large number of persons simultaneously by means of the Leyden jar. For this purpose they must form a chain by joining hands. If then the first touches the outside coating of a charged jar, whilst the last at the same time touches the knob, all receive a simultaneous shock, the intensity of which depends on the charge, and on the number of persons receiving it. Those in the centre of the chain are found to receive a less violent shock than those near the extremities. The Abbé Nollet discharged a Leyden jar through an entire regiment of 1500 men, who all received a violent shock in the arms and shoulders.

With large Leyden jars and batteries the shock is sometimes very dangerous. Priestley killed rats with batteries of 7 square feet coated surface, and cats with a battery of about $4\frac{1}{2}$ square yards coating.

708. **Luminous effects.**—The recomposition of two electricities of high tension is always accompanied by a disengagement of light, as is seen when sparks are taken from a machine, or when a Leyden jar is discharged. The better the conductors on which the electricities are accumulated the more brilliant is the spark; its colour varies not only with the nature of the bodies, but also with the nature of the surrounding medium and with the pressure. The spark between two charcoal points

is yellow, between two balls of silvered copper it is green, between knobs of wood or ivory it is crimson. In atmospheric air at the ordinary pressure the electric spark is white and brilliant; in rarefied air it is reddish; and in vacuo it is violet. In oxygen, as in air, the spark is white; in hydrogen it is reddish; and green in the vapour of mercury; in carbonic acid it is also green, while in nitrogen it is blue or purple, and accompanied by a peculiar sound. Generally speaking, the higher the tension the greater is the lustre of the spark. It is asserted by Fusinieri that in the electric spark there is always a transfer of material particles in a state of extreme tenuity, in which case the modifications in colour must be due to the transport of ponderable matter.

When the spark is viewed through a prism, the spectrum obtained is full of dark lines (513), the number and arrangement of which depend on the nature of the poles.

709. **Spark and brush discharge.**—The shapes which luminous electric phenomena assume may be classed under two heads—the *spark* and the *brush*. The brush forms when the electricity leaves the conductor in a continuous flow; the spark, when the discharge is discontinuous. The formation of one or the other of these depends on the nature of the conductor and on the nature of the conductor in its vicinity; and small alterations in the position of the surrounding conductors transform the one into the other.

The spark which at short distances appears straight, at longer distances has a zigzag-shape with diverging branches. Its length depends on the tension at the part of the conductor from which it is taken; and to obtain the longest sparks the electricity must be of as high tension as possible, but not so high as to discharge spontaneously. With long sparks the luminosity is different in different parts of the spark.

The brush derives its name from the radiating divergent arrangement of the light, and presents the appearance of a luminous cone, whose apex touches the conductor. Its size and colour differ with the nature and form of the conductor; it is accompanied by a peculiar hissing noise, very different from the sharp crack of the spark. Its luminosity is far less than that of the spark, for while the latter can easily be seen by daylight, the former is only visible in a darkened room. The brush discharge may be obtained by placing on the conductor a wire filed round at the end, or, with a powerful machine, by placing a small bullet on the conductor. The brush from a negative conductor is less than from a positive conductor; the cause of this difference has not been very satisfactorily made out, but originates probably in the fact which Faraday has observed, that negative electricity discharges into the air at a somewhat lower tension than positive electricity; so that a negatively charged knob sooner attains that tension at which spontaneous discharge takes place than does a positively charged one, and therefore discharges the electricity at smaller intervals and in less quantities.

When electricity in virtue of its high tension issues from a conductor, no other conductor being near, the discharge takes place without noise, and at the places at which it appears there is a pale blue luminosity,

called the *electrical glow*, or on points, a star-like centre of light. It is seen in the dark by placing a point on the conductor of the machine.

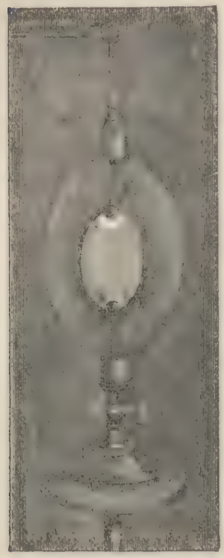


Fig. 566.

710. **Electric egg.**—The influence of the pressure of the air on the electric light may be studied by means of the *electric egg*. This consists of an ellipsoidal glass vessel (fig. 566), with metal caps at each end. The lower cap is provided with a stopcock, so that it can be screwed into an air pump, and also into a heavy metallic foot. The upper metallic rod moves up and down in a leather stuffing box; the lower one is fixed to the cap. A vacuum having been made, the stopcock is turned, and the vessel screwed into its foot; the upper part is then connected with a powerful electrical machine, and the lower one with the ground. On working the machine, the globe becomes filled with a feeble violet light continuous from one end to the other, and resulting from the recomposition of the positive fluid of the upper cap with the negative of the lower. If the air be gradually allowed to enter by opening the stopcock, the tension of the electricity increases with the resistance, and the light now appears white and brilliant, and is only seen as an ordinary intermittent spark.

Some beautiful effects of the electric light are obtained by means of Geissler's tubes, which will be noticed under Dynamical Electricity.

711. **Luminous tube, square, and bottle.**—The *luminous tube* (fig. 567) is a glass tube about a yard long, round which are arranged in

Fig. 567.

a spiral form a series of lozenge-shaped pieces of tin foil, between which are very short intervals. There is a brass cap which hooks at each end, in which the spiral terminates. If one end be presented to a machine in action, while the other is held in the hand, sparks appear simultaneously at each interval, and produce a brilliant luminous appearance, especially in the dark.

The *luminous pane* (fig. 568) is constructed on the same principle, and consists of a square of ordinary glass, on which is fastened a narrow strip

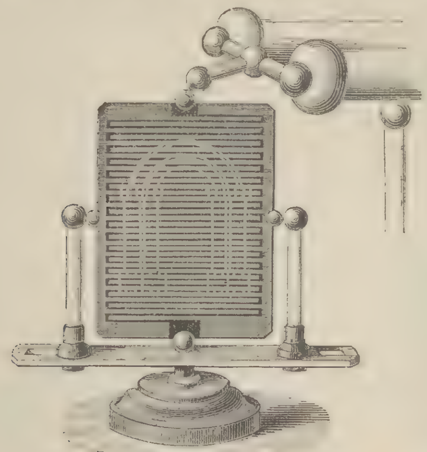


Fig. 568.

of tin foil folded parallel to itself for a great number of times. Spaces are cut out of this strip so as to represent any figure, a portico for example. The pane being fixed between two insulating supports, the upper extremity of the strip is connected with the electrical machine, and the lower part with the ground. When the machine is in operation, a spark appears at each interval, and reproduces in luminous flashes the object represented on the glass.

The *luminous jar* (fig. 569) is a Leyden jar, whose outer coating consists of a layer of varnish strewed over with metallic powder. A strip of tin fitted on the bottom is connected with the ground by means of a chain; a second band at the upper part of the coating has a projecting part, and the rod of the bottle is curved so that the knob is about $\frac{3}{4}$ of an inch distant from the projection. This bottle is suspended from the machine, and as rapidly as this is worked, large and brilliant sparks pass between the knob and the outer coating, illuminating the outside of the apparatus.

712. **Calorific effects.**—Besides being luminous, the electric spark is a source of intense heat. When it passes through inflammable liquids, as ether or alcohol, it inflames them. An arrangement for effecting this is represented in figure 570. It is a small glass cup through the bottom of which passes a metal rod, terminating in a knob and fixed to a metal foot. A quantity of liquid sufficient to cover the knob is placed in the vessel. The outer coating of the jar having been connected with the foot by means of a chain, the spark which passes when the two knobs are brought near each other inflames the liquid.

With ether the experiment succeeds very well, but alcohol requires to be first warmed.

Coal gas may also be ignited by means of the electric spark. A person

Fig. 569.

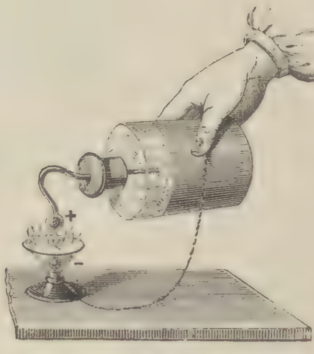


Fig. 570.

standing on an insulated stool places one hand on the conductor of a machine which is then worked, while he presents the other to the jet of gas issuing from a metallic burner. The spark which passes ignites the gas. When a battery is discharged through an iron or steel wire it becomes heated, and even made incandescent or melted, if the discharge is very powerful. The laws of this heating effect have been investigated independently by Harris and by Riess by means of the *electric thermometer.* This is essentially an air thermometer, across the bulb of which is a fine platinum wire. When a discharge is passed through the wire it becomes heated, expands the air in the bulb, and this expansion is indicated in the motion of the liquid along the graduated stem of the thermometer. In this way it has been found that the increase in temperature in the wire is proportional to the electric density multiplied by the quantity of electricity; and since the electric density is equal to the quantity of electricity, usually measured by the number of discharges of the unit jar (702), divided by the surface, the heating effect is proportional to the square of the number of discharges divided by the surface; that is, $h = \frac{q^2}{s}$.

Riess has also found that *with the same charge, but with wires of different dimensions, the rise of temperature is inversely as the fourth*

power of the diameter. Thus, compared with a given wire as unity, the *rise of temperature* in a wire of double or treble the diameter would be $\frac{1}{16}$ or $\frac{1}{81}$ as small; but as the masses of these wires are four and nine times as great, *the heat produced* would be respectively $\frac{1}{4}$ and $\frac{1}{9}$ as great as in a wire of unit thickness.

When an electric discharge is sent through gunpowder placed on the table of a Henley's discharger, it is not ignited, but is projected in all directions. But if a wet string be interposed in the circuit a spark passes which ignites the powder. This arises from the retardation which electricity experiences in traversing a semi-conductor, such as a wet string: for the heating effect is proportional to the duration of the discharge.

When a charge is passed through sugar, heavy spar, fluorspar, and other substances, they afterwards become phosphorescent in the dark. Eggs, fruit, etc., may be made luminous in the dark in this way.

When a battery is discharged through a gold leaf, pressed between two glass plates or between two silk ribbons, the gold is volatilised in a violet powder which is finely divided gold. In this way the electric portraits are obtained.

When a jar is charged and discharged several times in succession it becomes heated as Siemens has shown. Hence there must be movements of the molecules of the glass as Faraday supposed.

713. **Magnetic effects.**—By the discharge of a large Leyden jar or battery, a steel wire may be magnetised if it is laid at right angles to a

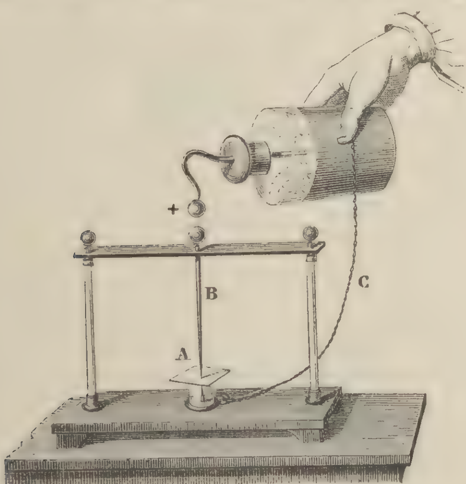


Fig. 571.

conducting wire through which the discharge is effected, either in contact with the wire or at some distance. And even with less powerful discharges a steel bar or needle may be magnetised by placing it in a tube on which

is coiled a fine insulated copper wire. On passing the discharge through this wire the steel becomes magnetised.

To effect a deflection of the magnetic needle by the electric current produced by frictional electricity is more difficult. It may be accomplished by making use of a galvanometer consisting of 400 or 500 turns of fine silk-covered wire, which is further insulated by being coated with shellac varnish, and by separating the layers by means of oiled silk. When the prime conductor of a machine in action is connected with one end of the galvanometer wire, and the other with the ground, a deflection of the needle is produced.

714. **Mechanical effects.**—The mechanical effects are the violent lacerations, fractures, and sudden expansions which ensue when a powerful discharge is passed through a badly-conducting substance. Glass is perforated, wood and stones are fractured, and gases and liquids are violently disturbed. The mechanical effects of the electric spark may be demonstrated by a variety of experiments.

Figure 571 represents an arrangement for perforating a piece of glass or card. It consists of two glass columns, with a horizontal cross-piece, in which is a pointed conductor, B. The piece of glass, A, is placed on an insulating glass support, in which is placed a second conductor, terminating also in a point, which is connected with the outside of the battery, while the knob of the inner coating is brought near the knob of B. When the discharge passes between the two conductors the glass is

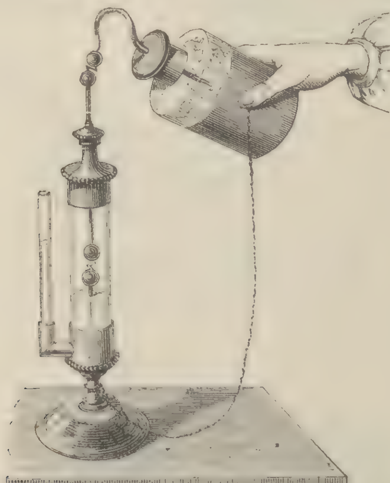


Fig. 572.

perforated. The experiment only succeeds with a single jar when the glass is very thin; otherwise a battery must be used.

The perturbation and sudden expansion which the discharge produces

may be illustrated by means of Kinnersley's thermometer. This consists of two glass tubes (fig. 572), which fit into metallic caps, and communicate with each other. At the top of the large tube is a rod terminating in a knob, and moving in a stuffing-box, and at the bottom there is a similar rod with a knob. The apparatus contains water up to the level of the lower knob. When the electric shock passes between the two knobs, the water is driven out of the larger tube and rises to a slight extent in the small one. The level is immediately re-established, and therefore the phenomenon is not due to an increase of temperature.

For the production of mechanical effects the universal discharger, fig. 560, is of great service. A piece of wood, for instance, placed on the table between the two conductors, is split when the discharge passes.

715. **Chemical effects.**—The chemical effects are the decompositions and recombinations effected by the passage of the electric discharge. Where two gases which act on each other are mixed in the proportions in which they combine, a single spark is often sufficient to determine their combination: but where either of them is in great excess, a succession of sparks is necessary. Priestley found that when a series of electric sparks was passed through moist air, its volume diminished, and blue litmus introduced into the vessel was reddened. This, Cavendish found, was due to the formation of nitric acid.

Several compound gases are decomposed by the continued action of the electric spark. With olefiant gas, sulphuretted hydrogen, and ammonia, the decomposition is complete; while carbonic acid is partially decomposed into oxygen aud carbonic oxide. The electric discharge also by suitable means can feebly decompose water, oxides, and salts; but though the same in kind, the chemical effects of statical electricity are by no means so powerful and varied as those of dynamical electricity. The chemical action of the spark is easily demonstrated by means of a solution of iodide of potassium. A small lozenge-shaped piece of filtering paper, impregnated with iodide of potassium, is placed on a glass plate, and one corner connected with the ground. When a few sparks from a conductor charged with positive electricity are taken at the other corner, brown spots are produced, due to the separation of iodine.

Among the chemical effects must be enumerated the formation of *ozone*, which is recognised by its peculiar odour and by certain chemical properties. The odour is perceived when electricity issues through a series of points from a conductor into the air. Its true nature is not accurately known: some regard it, and with great probability, as an allotropic modification of oxygen, and others as a teroxide of hydrogen.

The *electric pistol* is a small apparatus which serves to demonstrate the chemical effects of the spark. It consists of a brass vessel (fig. 573), in which is introduced a detonating mixture of two volumes of hydrogen and one of oxygen, and which is then closed with a cork. In a tubulure in the side there is a glass tube, in which fits a metallic rod, terminated by the knobs A and B. The knob is held as represented in fig. 574, and brought near the machine. The knob A becomes negatively, and B positively electrified by induction from the machine, and a spark passes

between the conductor and A. Another spark passes at the same time between the knob B and the side; this determines the combination of

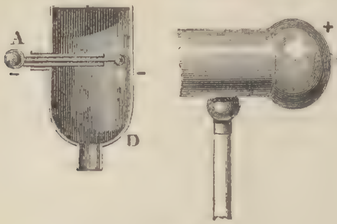


Fig. 573.

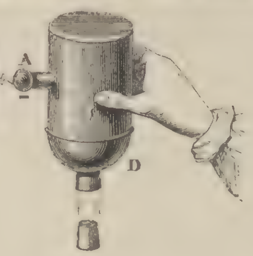


Fig. 574.

the gases, which is accompanied by a great disengagement of heat, and the vapour of water formed acquires such an expansive force, that the cork is projected with a report like that of a pistol.

716. **Application of the electrical discharge to firing mines.**—By the labours of Prof. Abel in this country, and of Baron von Ebner in Austria, the electrical discharge has been applied to firing mines for military purposes, and the methods have acquired a high degree of perfection. The principle on which the method is based may be understood from the following statement:

One end of an insulated wire in which is a small break is placed in contact with the outside of a charged Leyden jar, the other end being placed near the inner coating. If now this end be brought in contact with the inner coating the jar is discharged and a spark strikes across the break; and if there be here some explosive compound it is ignited, and this ignition may of course be communicated to any gunpowder in which it is placed. If on one side of the break, instead of having an insulated wire direct back to the outer coating of the Leyden jar, an uncovered wire be led into the ground, the outside of the jar being also connected with the ground, the result is unchanged, the earth acting as a return wire. Moreover, if there be several breaks, the explosion will still ensue at each of them, provided the charge be sufficiently powerful.

In the actual application it is of course necessary to have an arrangement for generating frictional electricity which shall be simple, portable, powerful, and working in any weather. In these respects the electrical machine devised by Von Ebner is admirable. Fig. 575 represents a view of this instrument as constructed by Messrs. Elliott, part of the case being removed to show the internal construction.

It consists of two circular plates of ebonite, *a*, mounted on an axis so that they are turned by a handle, *b*, between rubbers, which are so arranged as to be easily removed for the purposes of amalgamation, etc. Fastened to a knob on the base of the apparatus and projecting between the plates is a pointed brass rod, which acts as a collector of the electricity. The condenser or Leyden jar arrangement is inside the case, part of which has been removed to show the arrangement. It consists of

India-rubber cloth, coated on each side with tinfoil, and formed into a roll for the purpose of greater compactness. By means of a metal button

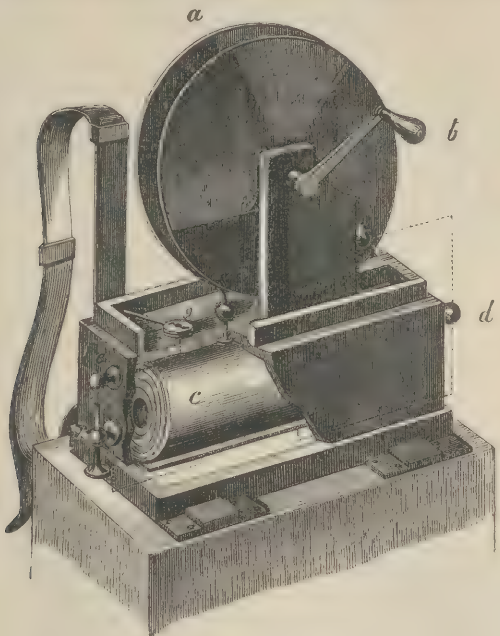


Fig. 575.

the knob is in contact with one tinfoil coating, which thus receives the electricity of the machine, and corresponds to the inner coating of the Leyden jar. Another button, connected with the other tinfoil coating, rests on a brass band at the base of the apparatus which is in metallic contact with the cushions, the knob *d*, and the perforated knob in which slides a rod at the front of the apparatus. These are all in connection with the earth. The knob *e* is in metallic connection with a disc *g* provided with a light arm. By means of a flexible chain this is so connected with a trigger on the side of the apparatus, not represented in the figure, that when the trigger is depressed, the arm, and therewith the knob *e*, is brought into contact with the inner coating of the condenser.

On depressing the trigger after a certain number of turns a spark passes between the knob *e* and the sliding rod, and the striking distance is a measure of the working condition of the instrument.

The fuse used is known as Abel's electrical fuse, and has the following construction. The ends of two fine copper wires, fig. 576, are imbedded in a thin solid gutta percha rod, parallel to each other, but at a distance of about 1·5 mim. At the lower end of the gutta percha a small cap of

paper or tinfoil *cc* is fastened, in which is placed a small quantity of the priming composition, which consists of an intimate mixture of subsulphide of copper, subphosphide of copper, and chlorate of potassium. The paper is fastened down so that the exposed ends of the wires are preserved in close contact with the powder.

This is the actual fuse; for service the capped end of the fuse is placed in a perforation in the rounded head of a wooden cylinder, so as to project slightly into the cavity *g* of the cylinder. This cavity is filled with meal powder which is well rammed down, so that the fuse is firmly imbedded. It is afterwards closed by a plug of gutta percha, and the whole is finally coated with black varnish.

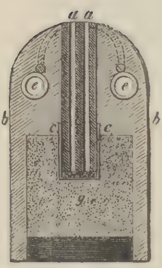


Fig. 576.

Fig. 577.

The free ends of the wires *a a* are pressed into small grooves in the head of the cylinder (fig. 577), and each end is bent into one of the small channels with which the cylinder is provided, and which are at right angles to the central perforation. They are wedged in here by driving in small copper tubes, the ends of which are then filed flush with the surface of the cylinder. The bared ends of two insulated conducting wires are then pressed into one of the small copper tubes or eyes, and fixed there by bending the wire round on to the wood, as shown at *e*.

The conducting wire used in firing may be thin, but it must be well insulated. One end, which is bared, having been pressed into the hole *d* of the fuse, the other is placed in proximity to the exploder. Into the other hole *d'* of the fuse a wire is placed which serves as earth wire, care being taken that there is no connection between the two wires. The fuse having been introduced into the charge the earth wire is placed in good

connection with the ground. The knob *f* of the exploder is also connected with the earth by leading uncovered wire into water or moist earth, and the condition of the machine tested. The end of the insulated wire is then connected with the knob *e* and the rod drawn down; at the proper signal the handle is turned the requisite number of times, and when the signal is given the trigger is depressed, and the explosion ensues.

When a number of charges are to be fired they are best placed in a single circuit, care being taken that the insulation is good.

717. **Duration of the electric spark. Velocity of electricity.**—Wheatstone has measured the duration of the electric spark, and the velocity of electricity, by means of the rotating mirror, which he invented for this purpose. At some distance from this instrument, which can be made to rotate with a measured velocity, a Leyden jar is so arranged that the spark of its discharge is reflected from the mirror. Now, from the laws of reflection (Note, art. 459) the image of the luminous point describes an arc of double the number of degrees which the mirror describes, in the time in which the mirror passes from the position in which the image is visible to that in which it ceases to be so. If the duration of the image were absolutely instantaneous the arc would be reduced to a mere point. Knowing the number of turns which the mirror makes in a second, and measuring, by means of a divided circle, the number of degrees occupied by the image, the duration of the spark would be determined. In one experiment Wheatstone found that this arc was 24°. Now, in the time in which the mirror traverses 360° the image traverses 720°; but in the experiment the mirror made 800 turns in a second, and therefore the image traversed 576,000° in this time; and as the arc was 24°, the image must have lasted the time expressed by $\frac{24}{576000}$ or $\frac{1}{24000}$ of a second. Thus the discharge is not instantaneous, but has a certain duration, which, however, is excessively short.

To determine the velocity of electricity, Wheatstone constructed an apparatus the principle of which will be understood from figure 578: six insulated metal knobs were arranged in a horizontal line on a piece of wood called the *spark board*; of these the knob 1 was connected with the outer, while 6 could be connected with the inner coating of a charged Leyden jar; the knob 1 was a tenth of an inch distant from the knob 2; while between 2 and 3 a quarter of a mile of insulated wire was interposed; 3 was likewise a tenth of an inch from 4, and there was a quarter of a mile of wire between 4 and 5; lastly, 5 was a tenth of an inch from 6, from which a wire led directly to the outer coating of the Leyden jar. Hence, when the jar was discharged by connecting the wire from 6 with the inner coating of the jar, sparks would pass between 1 and 2, between 3 and 4, and between 5 and 6. Thus the discharge, supposing it to proceed from the inner coating, has to pass in its course

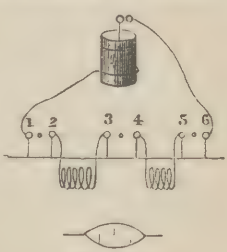


Fig. 578.

through a quarter of a mile of wire between the first and second spark, and through the same distance between the second and third.

The spark board was arranged at a distance of 10 feet from the rotating mirror, and at the same height, both being horizontal; and the observer looked down on the mirror. Thus the sparks were visible when the mirror made an angle of 45° with the horizon.

Now, if the mirror were at rest or had only a small velocity, the images of the three sparks would be seen as three dots ⋮, but when the mirror had a certain velocity these dots appeared as lines, which were longer as the rotation was more rapid. The greatest length observed was 24°, which, with 800 revolutions in a second, can be shown to correspond to a duration of $\frac{1}{24000}$ of a second. With a slow rotation the lines present the appearance ; they are quite parallel, and the ends in the same line. But with greater velocity, and when the rotation took place from left to right, they presented the appearance , and when it turned from right to left the appearance , because the image of the centre spark was formed after the lateral ones. Wheatstone found that this displacement amounted to half a degree before or behind the others. This arc corresponds to a duration of $\frac{1}{2 \times 720 \times 800}$ or $\frac{1}{1152000}$ of a second; the space traversed in this time being a quarter of a mile, gives for the velocity of electricity, 288,000 miles in a second, which is greater than that of light. The velocity of dynamical electricity is far less; and owing to induction, the transmission of a current through submarine wires is comparatively slow.

In the above experiment the images of the two outer sparks appear simultaneously in the mirror, from which it follows that the electric current issues simultaneously from the two coatings of the Leyden jar.

From certain theoretical considerations based upon measurements of constant electrical currents, Kirchhoff has concluded that the motion of electricity in a wire in which it meets with no resistance is like that of a wave on a stretched string, and has the velocity $V = \frac{4093159}{\sqrt{2}}$, or 192,924 miles in a second, which is about that of light in vacuo. According to Walker, the velocity of electricity is 18,400 miles, and, according to Fizeau and Gounelle, it is 62,100 miles in iron, and 111,780 in copper wire. These measurements, however, were made with telegraph wires, which induce opposite electricities in the surrounding media; there is thus produced a resistance which diminishes the velocity. The velocity is less therefore in water than in air. The nature of the conductor appears to have some influence on the velocity; but not the thickness of the wire, nor the tension of the electricity.

For atmospheric electricity, reference must be made to the chapter on Meteorology.

BOOK X.

DYNAMICAL ELECTRICITY.

CHAPTER I.

VOLTAIC PILE. ITS MODIFICATIONS.

718. **Galvani's experiment and theory.**—The fundamental experiment which led to the discovery of dynamical electricity is due to Galvani, professor of anatomy in Bologna. Occupied with investigations on the influence of electricity on the nervous excitability of animals, and especially

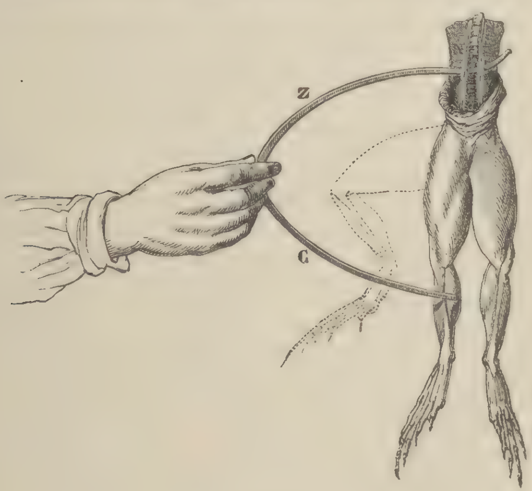


Fig. 579.

of the frog, he observed that when the lumbar nerves of a dead frog were connected with the crural muscles by a metallic circuit, the latter became briskly contracted.

To repeat this celebrated experiment, the legs of a recently killed frog are prepared, and the lumbar nerves on each side of the vertebral column

are exposed in the form of white threads. A metallic conductor, composed of zinc and copper, is then taken (fig. 579), and one end introduced between the nerves and the vertebral column, while the other touches one of the muscles of the thighs or legs; at each contact a smart contraction of the muscles ensues.

Galvani had some time before observed that the electricity of machines produced in dead frogs analogous contractions, and he attributed the phenomena first described to an electricity inherent in the animal. He assumed that this electricity, which he called *vital fluid*, passed from the nerves to the muscles by the metallic arc, and was thus the cause of contraction. This theory met with great support, especially among physiologists, but it was not without opponents. The most considerable of these was Alexander Volta, professor of physics in Pavia.

719. **Volta's fundamental experiment.**—Galvani's attention had been exclusively devoted to the nerves and muscles of the frog; Volta's was directed upon the connecting metal. Resting on the observation, which Galvani had also made, that the contraction is more energetic when the connecting arc is composed of two metals than when there is only one, Volta attributed to the metals the active part in the phenomenon of contraction. He assumed that the disengagement of electricity was due to their contact, and that the animal parts only officiated as conductors, and at the same time as a very sensitive electroscope.

By means of the then recently invented electroscope, Volta devised several modes of showing the disengagement of electricity on the contact of metals, of which the following is the easiest to perform:

The moistened finger being placed on the upper plate of a condensing electroscope (fig. 563), the lower plate is touched with a plate of copper, *c*, soldered to a plate of zinc, *z*, which is held in the other hand. On breaking the connection and lifting the upper plate (fig. 564), the gold leaves diverge, and, as may be proved, with negative electricity. Hence, when soldered together, the copper is charged with negative electricity, and the zinc with positive electricity. The electricity could not be due either to friction or pressure; for if the condenser plate, which is of copper, is touched with the zinc plate *z*, the copper plate to which it is soldered being held in the hand, no trace of electricity is observed.

A memorable controversy arose between Galvani and Volta. The latter was led to give greater extension to his contact theory, and propounded the principle that when *two heterogeneous substances are placed in contact, one of them always assumes the positive and the other the negative electrical condition.* In this form Volta's theory obtained the assent of the principal philosophers of his time. Galvani, however, made a number of highly interesting experiments with animal tissues. In some of these he obtained indications of contraction, even though the substances in contact were quite homogeneous. He thus discovered the existence of animal electricity, which, within the last few years, has been established by Matteucci, under the name of frog-current.

720. **Disengagement of electricity in chemical actions.**—The contact theory which Volta had propounded, and in which he explained

the action of the pile, soon encountered objectors. Fabroni, a countryman of Volta, having observed that in the pile the discs of zinc became oxidised in contact with the acidulated water, thought that this oxidation was the principal cause of the disengagement of electricity. In England Wollaston soon advanced the same opinion, and Davy supported it by many ingenious experiments.

It is true that in the fundamental experiment of the contact theory (719) Volta obtained signs of electricity. But M. de la Rive has shown that if the zinc be held in a wooden clamp, all signs of electricity disappear, and that the same is the case if the zinc be placed in gases, such as hydrogen or nitrogen, which exert upon it no chemical action. De la Rive has accordingly concluded that in Volta's original experiment the disengagement of electricity is due to the chemical actions which result from the perspiration and from the oxygen of the atmosphere.

The development of electricity in chemical actions may be demonstrated in the following manner by means of the condensing electroscope (704). A disc of moistened paper is placed on the upper plate of the condenser, and on this a zinc capsule, in which some dilute sulphuric acid is poured. A platinum wire, communicating with the ground, but insulated from the sides of the vessel, is immersed in the liquid, and at the same time the lower plate of the condenser is also connected with the ground by touching it with the moistened finger. On breaking contact and removing the upper plate, the gold leaves are found to be positively electrified, proving that the upper plate has received a charge of negative electricity due to the chemical action of the sulphuric acid on the zinc.

By a variety of analogous experiments it may be shown that all chemical actions are accompanied by a disturbance of the electrical equilibrium. This is the case whether the substances concerned in the action are in the solid, liquid, or gaseous state, though of all chemical actions those between metals and liquids are the most productive of electricity. All the various resultant effects may be explained on the general principle, that when a liquid acts chemically on a metal the liquid assumes the positive electrical, and the metal the negative electrical condition. In the above experiment the sulphuric acid, by its action on zinc, became positively electrified, and its electricity passed off through the platinum wire into the ground, while the negative electricity excited in the zinc acted on the condenser just as an excited rod of sealing-wax would have done.

In many cases the electrical indications accompanying chemical actions are of a very feeble nature, and require the use of a very delicate electroscope to render them sensible. Thus, one of the most energetic chemical actions, that of sulphuric acid upon zinc, gives no more free electricity than water alone does with zinc. In the former case, both the metal and the liquid are good conductors, and hence the two electricities tend to recombine directly at the place of their separation, instead of one passing into the earth and another into the condenser. Only a small portion escapes neutralisation, and it is this which the instruments indicate. It

is important not to confound the electricity generated with the electricity perceived.

721. **Current electricity.**—When a plate of zinc and a plate of copper are partially immersed in dilute sulphuric acid, a disturbance of the electrical equilibrium ensues, for, by means of delicate electroscopic arrangements, it may be shown that the zinc plate possesses a feeble charge of negative and the copper plate a feeble charge of positive electricity. At the same time there is a slight disengagement of hydrogen from the surface of the zinc. If now the plates be placed in direct contact, or, more conveniently, be connected by means of a metallic wire, the chemical action increases, but the hydrogen is now disengaged from the surface of the copper (fig. 580); and if the connecting wire be examined it will be found to possess many remarkable thermal, magnetic, and other properties, to be hereafter described. So long as the metals remain in the liquid, the opposite electrical conditions of the two plates discharge themselves by means of the wire, but are instantaneously restored, and as rapidly discharged; and as these successive charges and discharges take place at such infinitely small intervals of time that they may be considered continuous, the wire is said to be traversed by an electric or voltaic *current.* The direction of this current *in the connecting wire* is assumed to be from the copper to the zinc, or, in other words, this is the direction in which the positive electricity is supposed to flow, the direction of the negative current in the wire being from the zinc to the copper. But the existence of this current is purely hypothetical, and must not be taken as more than a convenient mode of explaining the phenomena developed in the wire.

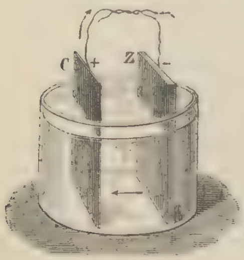


Fig. 580.

722. **Voltaic couple. Electromotive series.**—The arrangement just described, consisting of two metals in metallic contact, and a conducting liquid in which they are placed, constitutes a *simple voltaic element or couple.* So long as the metals are not in contact, the couple is said to be *open*, and when connected it is *closed.*

For the production of a voltaic current it is not necessary that one of the metals be unaffected by the liquid, but merely that the chemical action upon the one be greater than upon the other. For then, in accordance with what has been before stated (721), the two metals may be considered to give rise to two separate currents, of which the one proceeding from the metal most attacked is the stronger, and the current perceived is therefore the difference between two unequal currents. If the currents were absolutely equal, a condition, however, practically impossible to realise, we must assume that no electrical effects would be produced. The metal which is most attacked is called the *positive* or *generating* plate, and that which is least attacked the *negative* or *collecting* plate. The positive metal determines the direction of the current,

which proceeds *in* the liquid from the positive to the negative *plate*, and *out* of the liquid through the connecting wire from the negative to the positive plate.

In speaking of the direction of the current the positive current is always understood; to avoid confusion, the existence of the current in the opposite direction, the negative current, is tacitly ignored.

The mere immersion of two different metals in a liquid is not alone sufficient to produce a current, there must be chemical action. When a platinum and a gold plate are connected with a delicate galvanometer and immersed in pure nitric acid no current is produced; but on adding a drop of hydrochloric acid a strong current is excited, which proceeds in the liquid from the gold to the platinum, because the gold is attacked by the nitro-hydrochloric acid, while the platinum is less so, if at all.

As a voltaic current is produced whenever two metals are placed in metallic contact in a liquid which acts more powerfully upon one than upon the other, there is great choice in the mode of producing such currents. In reference to their electrical deportment, the metals have been arranged in what is called an *electromotive series*, in which the most *electropositive* are at one end, and the most *electronegative* at the other. Hence when any two of these are placed in contact in dilute acid, the current in the connecting wire proceeds from the one lower in the list to the one higher. The principal metals are as follows:—

Zinc	Nickel	Gold
Cadmium	Bismuth	Platinum
Tin	Antimony	Graphite
Lead	Copper	
Iron	Silver	

It will be seen that the electrical deportment of any metal depends on the metal with which it is associated. Iron, for example, in dilute sulphuric acid is electronegative towards zinc, but is electropositive towards copper; copper in turn is electronegative towards iron and zinc, but electropositive towards silver, platinum, or graphite.

723. **Electromotive force.**—The force produced by the difference in chemical action on two metals in a liquid is called the *electromotive force*; it is greater in proportion to the distance of the two metals from one another in the series. That is to say, it is greater, the greater the difference between the chemical action upon the two metals immersed. Thus the electromotive force between zinc and platinum is greater than that between zinc and iron, or between zinc and copper. The law established by Poggendorff is, that *the electromotive force between any two metals is equal to the sum of the electromotive forces between all the intervening metals.* Thus the electromotive force between zinc and platinum is equal to the sum of the electromotive forces between zinc and iron, iron and copper, and copper and platinum.

The electromotive force is influenced by the condition of the metal; rolled zinc, for instance, is negative towards cast zinc. It also depends on the degree of concentration of the liquid; in dilute nitric acid zinc is

positive towards tin, and mercury positive towards lead; while in concentrated nitric acid the reverse is the case, mercury and zinc being respectively electronegative towards lead and tin.

The nature of the liquid also influences the direction of the current. If two plates, one of copper and one of iron, are immersed in dilute sulphuric acid, a current is set up proceeding through the liquid from the iron to the copper; but if the plates, after being washed, are placed in solution of sulphide of potassium, a current is produced in the opposite direction, the copper is now the positive metal. Other examples may be drawn from the following table, which shows the electric deportment of the principal metals with three different liquids. It is arranged like the preceding one; each metal being electropositive towards any one lower in the list, and electronegative towards any one higher.

Caustic potass	Hydrochloric acid	Sulphide of potassium
Zinc	Zinc	Zinc
Tin	Cadmium	Copper
Cadmium	Tin	Cadmium
Antimony	Lead	Tin
Lead	Iron	Silver
Bismuth	Copper	Antimony
Iron	Bismuth	Lead
Copper	Nickel	Bismuth
Nickel	Silver	Nickel
Silver	Antimony	Iron

A voltaic current may also be produced by means of two liquids and one metal. This may be shown by the following experiment: In a beaker containing strong nitric acid is placed a small porous cylinder closed at one end, and containing strong solution of caustic potass. If now two platinum wires connected with the two ends of a galvanometer (709) are immersed respectively in the alkali and in the acid, a voltaic current is produced proceeding in the wire from the nitric acid to the potass, which thus correspond respectively to the negative and positive plates in ordinary couple.

A metal which is acted upon by a liquid can be protected from solution by placing in contact with it a more electropositive metal, and thus forming a simple voltaic circuit. This principle is the basis of Davy's proposal to protect the copper sheathing of ships, which are rapidly acted upon by sea water. If zinc or iron be connected with the copper, these metals are dissolved and the copper protected. Davy found that a piece of zinc the size of a nail was sufficient to protect a surface of forty or fifty square inches, but unfortunately the proposal has not been of practical value, for the copper must be attached to a certain extent to prevent the adherence of marine plants and shellfish.

724. **Poles and electrodes.**—If the wire connecting the two terminal plates of a voltaic couple be cut, it is clear, from what has been said about the origin and direction of the current, that positive electricity will

tend to accumulate at the end of the wire attached to the copper or negative plate, and negative electricity on the wire attached to the zinc or positive plate. These terminals have been called the *poles* of the battery. For experimental purposes, more especially in the decomposition of salts, plates of platinum are attached to the ends of the wires. Instead of the term poles the word *electrode* (ἤλεκτρον and ὁδὸς, a way) is now commonly used; for these are the *ways* through which the respective electricities emerge. It is important not to confound the positive *plate* with the positive *pole* or *electrode*. The positive electrode is that connected with the negative plate, while the negative electrode is connected with the positive plate.

725. **Voltaic pile. Voltaic battery.**—When a series of voltaic elements or pairs are arranged in such a manner that the zinc of one element is connected with the copper of another; the zinc of this with the copper of another, and so on, such an arrangement is called a *voltaic battery;* and by its means the effects produced by a single element are capable of being very greatly increased.

The earliest of these arrangements was devised by Volta himself. It consists (fig. 581) of a series of discs piled one over the other in the following order: at the bottom, on a frame of wood, is a disc of copper, then a disc of cloth moistened by acidulated water or by brine, then a disc of zinc; on this a disc of copper, and another disc of moistened cloth, to which again follow as many sets of zinc-cloth-copper, always in the same order, as may be convenient, the highest disc being of zinc. The discs are kept in vertical positions by glass rods, and it is convenient to have the discs of copper and zinc soldered together as represented in the diagram.

The terminal discs however are single, the one at the top being of zinc and that at the bottom of copper.

It will be readily seen that we have here a series of simple voltaic couples, the moistened disc acting as the liquid, and that the terminal zinc is the negative and the terminal copper the positive pole. From the mode of its arrangement, and from its discoverer, the apparatus is known as the *voltaic pile*, a term applied to all apparatus of this kind for accumulating the effects of dynamical electricity.

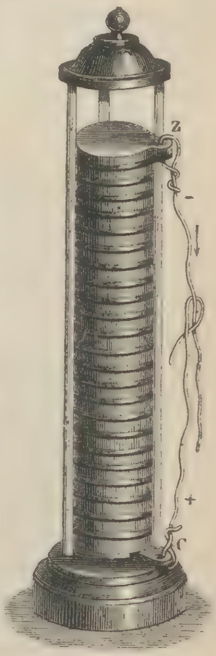


Fig. 581.

The distribution of electricity in the pile varies according as it is in connection with the ground by one of its extremities, or as it is insulated by being placed on a nonconducting cake of resin or glass.

In the former case, the end in contact with the ground is neutral, and the rest of the apparatus only contains one kind of electricity; this is negative if a copper disc is in contact with the ground, and positive if it is a zinc disc.

In the insulated pile the electricity is not uniformly distributed. By means of the proof-plane and the electroscope it may be demonstrated that the middle part is in a neutral state, and that one-half is charged with positive and the other with negative electricity, the tension increasing from the middle to the ends. The half terminated by a zinc is charged with negative electricity, and that by a copper with positive electricity. The pile is thus similar to a charged Leyden jar; with this difference however, that when the jar has been discharged by connecting its two coatings, the electrical effects cease; while in the case of the pile, the cause which originally brought about the distribution of electricity restores this state of charge after the discharge; and these successive charges and discharges are continuous; they form the current. The effects of the pile will we discussed in other places.

The original form of the voltaic pile has a great many inconveniences, and possesses now only an historical interest. It has received a great many improvements, the principal object of which has been to facilitate manipulation, and to produce greater electromotive force.

One of the earliest of these modifications was the crown of cups, or *couronne des tasses*, invented by Volta himself; an improved form of this is known as *Wollaston's battery* (fig. 582); it is arranged so that when the current is not wanted, the action of the battery can be stopped.

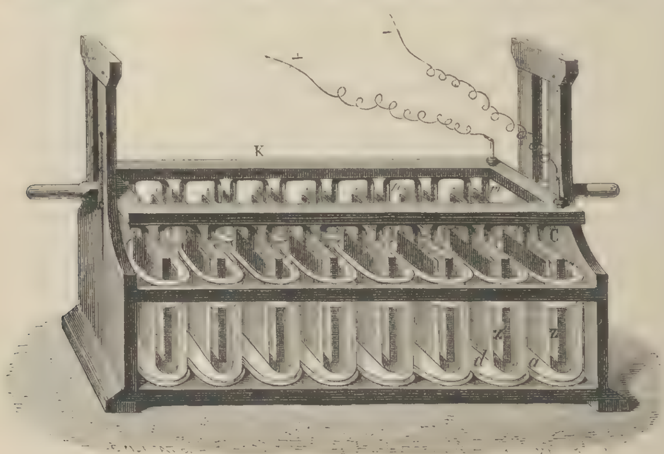


Fig. 582

The plates Z are of thick rolled zinc, and usually about eight inches in length by six in breadth. The copper plates C are of thin sheet, and bent so as to surround the zincs without touching them: contact being

prevented by small pieces of cork. To each copper plate a narrow strip of copper, *o*, is soldered, which is bent twice at right angles and is soldered to the zinc plate; and first zinc Z is surrounded by the first copper C; these two constitute a couple, and each couple is immersed in a glass vessel, containing acidulated water. The copper C is soldered to the second zinc by the strip *o*, and this zinc is in turn surrounded by a second copper, and so on.

Figure 582 represents a pile of sixteen couples united in two parallel series of eight each. All these couples are fixed to a cross frame of wood, by which they can be raised or lowered at pleasure. When the battery is not wanted, the couples are lifted out of the liquid. The water in these vessels is usually acidulated with $\frac{1}{16}$ sulphuric and $\frac{1}{20}$ of nitric acid.

Hare's deflagrator. This is a simple voltaic arrangement, consisting of two large sheets of copper and zinc rolled together in a spiral, but preserved from direct contact by bands of leather or horsehair. The whole is immersed in a vessel containing acidulated water, and the two plates are connected outside the liquid by a conducting wire.

726. **Enfeeblement of the current in batteries. Secondary currents. Polarity.**—The various batteries already described, Volta's, Wollaston's, and Hare's, which consist essentially of two metals and one liquid, labour under the objection that the currents produced rapidly diminish in intensity.

This is principally due to three causes; the first is the decrease in the chemical action owing to the neutralisation of the sulphuric acid by its combination with the zinc. This is a necessary action, for upon it depends the current; it therefore occurs in all batteries, and is without remedy except by replacement of acid and zinc. The second is due to what is called *local action*; that is, the production of small closed currents in the active metal, from the impurities it contains. These local currents rapidly wear away the active plate, without contributing anything to the general current. They are remedied by amalgamating the zinc with mercury, by which chemical action is prevented until the up circuit is closed, as will be more fully explained (735). The third arises from *secondary currents*. These are currents which are produced in the battery in a contrary direction to the principal current, and which destroy it either totally or partially. In the fundamental experiment (fig. 580), when the current is closed, sulphate of zinc is formed, which dissolves in the liquid, and at the same time a layer of hydrogen gas is gradually deposited on the surface of the copper plate. Now it has been found that the hydrogen deposited in this manner on metallic surfaces acts far more energetically than ordinary hydrogen. In virtue of this increased activity it gradually reduces some of the sulphate of zinc formed, and a layer of metallic zinc is formed upon the copper; hence, instead of having two different metals unequally attacked, the two metals become gradually less different, and, consequently, in the wire there are two currents tending to become equal; the total effect, and the current really observed, become weaker and weaker.

The *polarisation* of the plate (as this phenomenon is termed) may be

destroyed by breaking the circuit; the deposit then dissolves, and on again closing the circuit the intensity increases. The same result is obtained when the current of another battery is transmitted in a direction opposite to that of the first.

De la Rive found that when the platinum electrodes which had been used in decomposing a liquid were removed from this liquid and placed in distilled water, they produced a current when connected, in a direction opposite to that which they had at first transmitted. He calls this the *polarisation of the electrodes.* Becquerel and Faraday have shown that this polarity of the metals results from the deposits produced by secondary currents.

Platinum electrodes, however, which have been used to decompose pure water, may also become polarised. This phenomenon, as Matteucci has shown, arises from a deposit of hydrogen on the one, and of oxygen on the other electrode.

CONSTANT CURRENTS.

727. **Constant currents.**—With one or two exceptions, batteries composed of elements with a single liquid have gone almost entirely out of use, in consequence of the rapid enfeeblement of the current produced. They have been replaced by batteries with two liquids, which are called *constant batteries*, because their action is without material alteration for a considerable period of time. The essential point to be attended to in securing a constant current is to prevent the polarisation of the inactive metal; in other words, to hinder any permanent deposition of hydrogen on its surface. This is effected by placing the inactive metal in a liquid upon which the deposited hydrogen can act chemically.

728. **Daniell's battery.**—This was the first form of the constant battery, and was invented by Daniell in the year 1836. As regards the constancy of its action, it is still the best of all constant batteries. Fig. 583 represents a single element. A glass or porcelain vessel, V, contains a saturated solution of sulphate of copper, in which is immersed a copper cylinder, C, open at both ends, and perforated by holes. At the upper part of this cylinder there is an annular shelf, G, also perforated by small holes, and below the level of the solution: this is intended to support crystals of sulphate of copper to replace that decomposed as the electrical action proceeds. Inside the cylinder is a thin porous vessel, P, of unglazed earthenware. This contains either solution of common salt or dilute sulphuric acid, in which is placed the cylinder of amalgamated zinc, Z. Two thin strips of copper, *p* and *n*, fixed by binding screws to the copper and to the zinc, serve for connecting the elements in series.

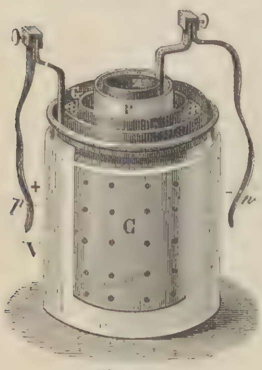


Fig. 583.

When a Daniell's element is closed, the hydrogen resulting from the action of the dilute acid on the zinc is liberated on the surface of the copper plate, but meets there the sulphate of copper, which is reduced, forming sulphuric acid and metallic copper, which is deposited on the surface of the copper plate. In this way sulphate of copper in solution is taken up, and if it were all consumed, hydrogen would be deposited on the copper, and the current would lose its constancy. This is prevented by the crystals of sulphate of copper which keep the solution saturated. The sulphuric acid produced by the decomposition of the sulphate permeates the porous cylinder, and tends to replace the acid used up by its action on the zinc; and as the quantity of sulphuric acid formed in the solution of sulphate of copper is regular, and proportional to the acid used in dissolving the zinc, the action of this acid on the zinc is regular also, and thus a constant current is produced.

In order to join together several of these elements to form a battery, the zinc of one is connected either by a copper wire or strip with the copper of the next, and so on, from one element to another, as shown in fig. 587, for another kind of battery.

Instead of a porous vessel a bag of sailcloth may be used for the diaphragm separating the two liquids. The effect is at first more powerful, but the two solutions mix more rapidly, which weakens the current. The object of the diaphragm is to allow the current to pass, but to prevent as much as possible the mixture of the two liquids.

The current produced by a Daniell's battery is constant for some hours; its action is stronger when it is placed in hot water

729. **Grove's battery.**—In this battery the sulphate of copper solution is replaced by nitric acid, and the copper by platinum, by which greater electromotive force is obtained. Fig. 584 represents one of the forms of a couple of this battery. It consists of a glass vessel, A, partially filled with dilute sulphuric acid (1 : 8); of a cylinder of zinc, Z, open at both ends; of a vessel, V, made of porous pipeclay, and containing ordinary nitric acid; of a plate of platinum, P (fig. 585), bent in the form of an S, and fixed to a cover, *c*, which rests on the porous vessel. The platinum is connected with a binding screw, *b*, and there is a similar binding screw on the zinc. In this battery the hydrogen, which would be disengaged on the platinum, meeting the nitric acid, decomposes it, forming hyponitrous acid, which dissolves or is disengaged as nitrous fumes. Grove's battery is the most convenient and one of the most powerful of the two-fluid batteries. It is, however, the most expen-

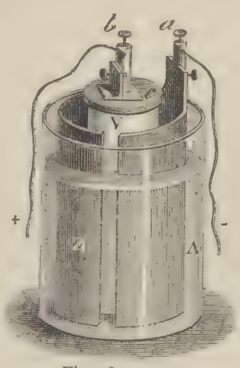


Fig. 584.

Fig. 585.

sive, owing to the high price of platinum; besides which the platinum is liable, after some time, to become brittle and break very easily. But as the platinum is not consumed, it retains its value; and M. Adam has shown that when the plates which have been used in a battery are heated to redness, they retain their elasticity.

730. **Bunsen's battery.**—*Bunsen's battery*, also known as the *zinc carbon* battery, was invented in 1843; it is nothing more than Grove's battery, in which the sheet of platinum is replaced by a cylinder of carbon. This is made either of the graphitoidal carbon deposited in gas retorts, or by calcining in an iron mould an intimate mixture of coke and bituminous coal, finely powdered and strongly compressed. Both these modifications of carbon are good conductors. Each element consists of the following parts: 1. a vessel, F (fig. 586), either of stoneware or of glass, containing dilute sulphuric acid; 2. a hollow cylinder, Z, of amalgamated zinc; 3. a porous vessel, V, in which is ordinary nitric acid; 4.

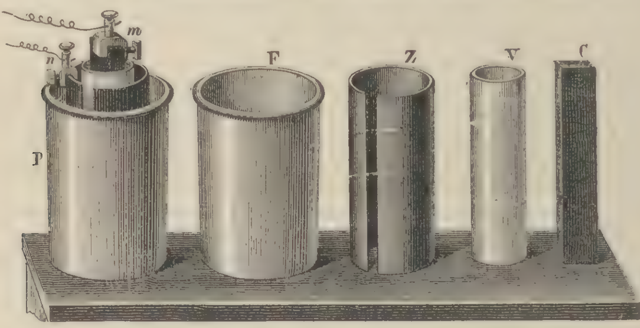


Fig. 586.

a cylinder of carbon, C, prepared in the above manner. In the vessel F the zinc is first placed, and in it the carbon as seen in P. To the carbon is fixed a binding screw, *m*, to which a copper wire is attached; forming the positive pole. The zinc is provided with a similar binding screw, *n*, and wire, which is thus a negative pole.

The elements are arranged to form a battery by connecting each carbon to the zinc of the following one by means of the clamps *mn* and a strip of copper *c* represented in the top of the figure. The copper is pressed at one end between the carbon and the clamp, and at the other it is soldered to the clamp *n* which is fitted on the zinc of the following element, and so forth. The clamp of the first carbon and that of the last zinc are alone provided with binding screws to which are attached the wires.

The chemical action of Bunsen's battery is the same as that of Grove's, and being equally powerful, while less costly, is almost universally used on the Continent. But though its first cost is less than that of Grove's battery, it is more expensive to work, and is not so convenient to manipulate.

Callan's battery is a modified form of Grove's. Instead of zinc and

platinum, zinc and platinised lead are used, and instead of pure nitric acid Callan uses a mixture of sulphuric acid, nitric acid, and saturated solution of nitre. The battery is said to be equal in its action to Grove's, and is much cheaper.

Callan has also constructed a battery in which zinc in dilute sulphuric acid forms the positive plate, and cast iron in strong nitric acid the negative. Under these circumstances the iron becomes passive; it is strongly electronegative, and does not dissolve. If, however, the nitric acid becomes

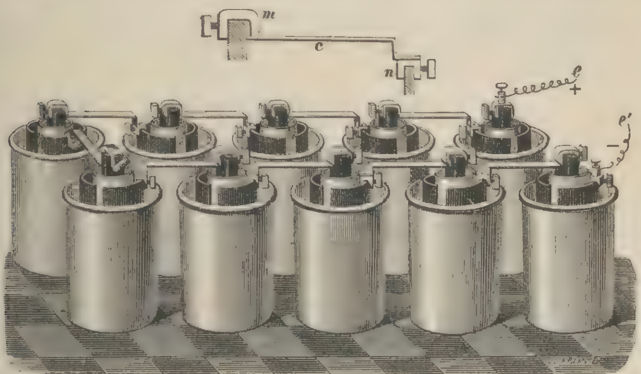


Fig. 587.

too weak, the iron is dissolved with simultaneous disengagement of nitrous fumes.

After being in use some time, all the batteries in which the polarisation is prevented by nitric acid disengage nitrous fumes in large quantities, and this is a serious objection to their use, especially in closed rooms. To prevent this, nitric acid is frequently replaced by chromic acid, or better, by a mixture of 4 parts bichromate of potassium, 4 parts sulphuric acid, and 18 water. The liberated hydrogen reduces the chromic acid to the state of oxide of chromium, which remains dissolved in sulphuric acid. With the same view, sesquichloride of iron is sometimes substituted for nitric acid; it becomes reduced to protochloride. But the action of the elements thus modified is considerably less than when nitric acid is used, owing to the increased resistance.

731. **Smee's battery.**—In this battery the polarisation of the negative plate is prevented by mechanical means. Each element consists of a sheet of platinum placed between two vertical plates of zinc, as in Grove's battery; but as there is only a single liquid, dilute sulphuric acid, the elements have much the form of those in Wollaston's battery. The adherence of hydrogen to the negative plate is prevented by covering the platinum with a deposit of finely divided platinum. In this manner the surface is roughened, which facilitates the disengagement of hydrogen to a remarkable extent, and, consequently, diminishes the resistance of the couple.

Instead of platinum, silver covered with a deposit of finely divided platinum is frequently substituted, as being cheaper.

Walker's battery.—This resembles Smee's battery, but the electronegative plate is either gas graphite or platinised graphite ; it is excited by dilute sulphuric acid. This battery is used in all the stations of the South Eastern Railway, and promises to come into more extensive use, for it has considerable electromotive force ; it is convenient and economical in manipulation, and large-sized elements can be constructed at a cheap rate.

732. **Recent batteries.**—The *sulphate of mercury* battery (fig. 588) devised by M. Marié Davy, is essentially a zinc-carbon element, but of smaller

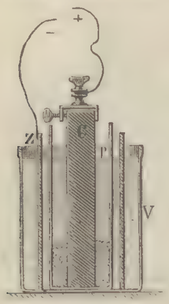


Fig. 588.

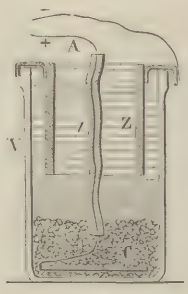


Fig. 589.

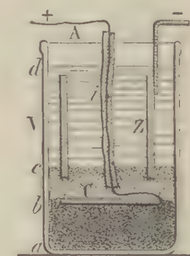


Fig. 590.

dimensions than those elements usually are. In the outer vessel V ordinary water or brine is placed, and in the porous vessel sulphate of mercury. This salt is agitated with about three times its volume of water, in which it is difficultly soluble, and the liquid poured off from the pasty mass. The carbon being placed in the porous vessel the spaces are filled with the residue and then the decanted liquid poured into it.

Chemical action takes place only when the pile is closed. The zinc then decomposes the water, liberating hydrogen, which traversing the porous vessel reduces the sulphate of mercury, forming metallic mercury, which collects at the bottom of the vessel, while the sulphuric acid formed at the same time traverses the diaphragm to act on the zinc and thus increases the action. The mercury which is deposited may be used to prepare a quantity of sulphate equal to that which has been consumed. A small quantity of the solution of sulphate of mercury may also pass through the diaphragm ; but this is rather advantageous, as its effect is to amalgamate the zinc.

The electromotive force of this element is about a quarter greater than that of Daniell's element, but it has greater resistance ; it is rapidly exhausted when continuously worked, though it appears well suited for discontinuous work, as with the telegraph, and with alarums.

Gravity batteries. The use of porous vessels is liable to many objections, more especially in the case of Daniell's battery, in which they gradually become encrusted with copper, which destroys them. A kind of

battery has been devised in which the porous vessel is entirely dispensed with, and the separation of the liquids is effected by their difference of density. Such batteries are called *gravity batteries*; the one in use at the telegraphic establishment of the Royal Engineers at Chatham is based on this principle.

Figure 589 represents a form devised by M. Callaud of Nantes. V is a glass or earthenware vessel in which is a copper plate soldered to a wire insulated by gutta percha. On the plate is a layer of crystals of sulphate of copper C; the whole is then filled with water, and the zinc cylinder Z is immersed in it. The lower part of the liquid becomes saturated with sulphate of copper; the action of the battery is that of a Daniell, and the sulphate of zinc which gradually forms floats on the solution of sulphate of copper owing to its lower density.

This battery is easily manipulated, the consumption of sulphate of copper is economical, and when not agitated it works constantly for some months, provided care be taken to replace the water lost by evaporation.

Menotti's battery. This may be described as a Daniell's element, in which the porous vessel is replaced by a layer of sawdust or of sand. At the bottom of an earthenware vessel (fig. 590) is placed a layer of coarsely-powdered sulphate of copper *a*, and on this a copper plate provided with an insulated copper wire *i*. On this there is a layer of sand or of sawdust *bc*, and then the whole is filled with water in which rests a zinc cylinder Z. The action is just that of a Daniell; the sand prevents the mixture of the liquids but it also offers great resistance, which increases with its thickness.

This battery is coming into use for telegraphic work, and from its simplicity and economy, and the facility with which it is constructed, merits increased attention.

Leclanché's elements consist of a rod of carbon placed in a porous pot, which is then tightly packed with a mixture of pyrolusite (peroxide of manganese) and coke. The porous pot is contained in an outer vessel in which is the electropositive element the zinc. The exciting liquid is a solution of sal ammoniac. The battery is coming into very extended use; its electromotive force is about $\frac{9}{10}$ that of a Daniell, and its resistance about $1\frac{1}{4}$ of a British Association unit.

733. **Electromotive force of different elements.**—The following values have been obtained for the electromotive force of the most usual combinations; they are the means of many careful determinations.

Bunsen's element	839
Grove's „	829
Daniell's „	470
Smee's „	210
Wollaston's „	208

734. **Tension of the battery.**—The tension of the battery is usually defined as being the tendency of the electricity accumulated at the extremities to free itself, and to overcome the obstacles offered to its

passage. It is proportional to the electromotive force : thus the tension of a zinc-carbon battery is greater than that of a zinc-copper battery. The tension of a battery must not be confounded with the *quantity* of electricity which it can disengage. The tension of a battery is proportional to the number of couples, while the quantity, other things being equal, is proportional to their surface. The larger this surface the greater is the quantity of electricity which flows in the circuit. This quantity also increases with the conductivity of the liquid interposed between the couples ; the tension on the contrary is independent of the nature of this liquid.

Except in the case of a very considerable number of couples, the tension at the extremities of the battery is always far weaker than in electrical machines.

Gassiott's great battery, which consisted of 3520 zinc and copper elements, with poles $\frac{1}{50}$ of an inch apart, gave a series of sparks across this interval which lasted for weeks.

By means of a delicate condensing electroscope, and by extremely careful insulation, the tension of a battery and even of a single cell may be observed. For this purpose one of the plates of the electroscope is connected with one end of the pile, and the other with the other end or with the ground. The apparatus is then charged, and on breaking the communications electroscopic indications are observed. A Leyden jar may even be charged when the interior coating is connected with one end of the pile, and the external coating with the other ; but the tension of this charge is far feebler than that furnished by an electrical machine.

On the other hand, the quantity of electricity which is furnished by a voltaic element is very great as compared with that of the machine. Faraday immersed two wires, one of zinc and the other of platinum, each $\frac{1}{18}$ of an inch in diameter, in acidulated water for $\frac{3}{20}$ of a second. The effect thus produced on a magnetic needle in this short time was greater than that produced by 23 turns of the large electrical machine of the Royal Institution.

735. **Amalgamated zinc. Local currents.**—De la Rive observed that perfectly pure distilled zinc was not attacked by dilute sulphuric acid, but became so when immersed in that liquid in contact with a plate of copper or of platinum. Ordinary commercial zinc, on the contrary, is rapidly dissolved by dilute acid. This, doubtless, arises from the impurity of the zinc, which always contains traces either of iron or lead. Being electronegative towards zinc they tend to produce *local electrical currents*, which accelerate the chemical action without increasing the quantity of electricity in the connecting wire.

Zinc, when amalgamated, acquires the properties of perfectly pure zinc, and is unaltered by dilute acid, so long as it is not in contact with a copper or platinum plate immersed in the same liquid. To amalgamate a zinc plate, it is first immersed in dilute sulphuric or hydrochloric acid so as to obtain a clean surface, and then a drop of mercury is placed on the plate and spread over it with a brush. The

amalgamation takes place immediately, and the plate has the brilliant aspect of mercury.

Zinc plates may also be amalgated by dipping them in a solution of mercury prepared by dissolving at a gentle heat one pound of mercury in five pounds of aqua regia (one part of nitric to three of hydrochloric acid), and then adding five parts more of hydrochloric acid.

The amalgamation of the zinc removes from its surface all the impurities, especially the iron. The mercury effects a solution of pure zinc, which covers the surface of the plate, as with a liquid layer.

The amalgamation of zinc was first applied to electrical batteries by Kemp. Amalgamated zinc is not attacked so long as the circuit is not closed, that is, when there is no current. With amalgamated zinc the current is more regular, and at the same time more intense, for the same quantity of metal dissolved.

736. **Dry piles.**—In *dry piles* the liquid is replaced by a solid hygrometric substance, such as paper or leather. They are of various kinds; in Zamboni's, which is most extensively used, the electromotors are tin or silver, and binoxide of manganese. To construct one of these a piece of paper silvered or tinned on one side is taken; the other side of the paper is coated with finely-powdered binoxide of manganese by slightly moistening it, and rubbing the powder on with a cork. Having placed together seven or eight of these sheets, they are cut by means of a punch into discs an inch in diameter. These discs are then arranged in the same order, so that the tin or silver of each disc is in contact with the manganese of the next. Having piled up 1,200 to 1,800 couples, they are placed in a glass tube, which is provided with a brass cap at each end. In each cap there is a rod and knob, by which the leaves can be pressed together, so as to produce better contact. The knob in contact with the manganese corresponds to the positive pole, while that at the other end, which is in contact with the silver or tin, is the negative pole.

The dry piles are remarkable for the permanence of their action, which may continue for several years. Their action depends greatly on the temperature and on the hygrometric state of the air. It is stronger in summer than in winter, and the action of a strong heat revives it when it appears extinct. A Zamboni's pile of 2,000 couples gives neither shock nor spark, but can charge a Leyden jar and other condensers. A certain time is however necessary, for electricity only moves slowly in the interior.

737. **Bohnenberger's electroscope.**—Bohnenberger has constructed a dry-pile electroscope of extreme delicacy. It is a condensing electroscope (fig. 563), from the rod of which is suspended a single gold leaf. This is at an equal distance from the opposite poles of two dry piles placed vertically, inside the bell jar, on the plate of the apparatus. As soon as the gold leaf possesses any free electricity it is attracted by one of the poles and repelled by the other, and its electricity is obviously contrary to that of the pole towards which it moves.

CHAPTER II.

DETECTION AND MEASUREMENT OF VOLTAIC CURRENTS.

738. **Detection and measurement of voltaic currents.**—The remarkable phenomena of the voltaic battery may be classed under the heads physiological, chemical, mechanical, and physical effects; and these latter may be again subdivided into the thermal, luminous, and magnetic effects. For ascertaining the existence and measuring the intensity of voltaic currents, the magnetic effects are more suitable than any of the others, and, accordingly, the fundamental magnetic phenomena will be described here, and the description of the rest postponed to a special chapter on electro-magnetism.

739. **Oersted's experiment.**—Oersted published in 1819 a discovery which connected magnetism and electricity in a most intimate manner, and became, in the hands of Ampère and of Faraday, the source of a new branch of physics. The fact discovered by Oersted is the directive action which a fixed current exerts at a distance on a magnetic needle.

To make this experiment a copper wire is suspended horizontally in the direction of the magnetic meridian over a moveable magnetic needle, as represented in fig. 591. So long as the wire is not traversed by a current the needle remains parallel to it, but as soon as the ends of the wire are respectively connected with the poles of a battery or of a single element, *the needle is deflected, and tends to take a position which is the more nearly at right angles to the magnetic meridian in proportion as the current is more intense.*

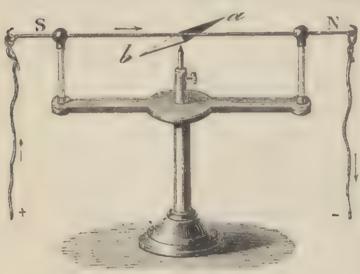


Fig. 591.

In reference to the direction in which the poles are deflected, there are several cases which may, however, be referred to a single principle. Remembering our assumption (722), that in the connecting wire the current proceeds from the negative to the positive plate, the preceding experiment presents the following four cases :—

i. If the current passes above the needle, and goes from south to north, the north pole of the magnet is deflected towards the west ; this arrangement is represented in the above figure.

ii. If the current passes below the needle, also from south to north, the north pole is deflected towards the east.

iii. When the current passes above the needle, but from north to south, the north pole is deflected towards the east.

iv. Lastly, the deflection is towards the west when the current goes from north to south below the needle.

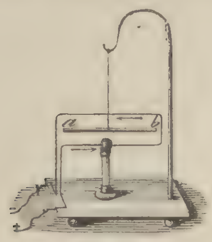


Fig. 592.

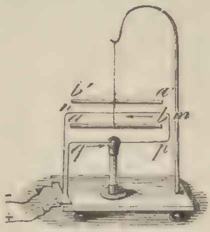


Fig. 593.

Ampère has given the following *memoria technica* by which all the various directions of the needle under the influence of a current may be remembered. If we imagine an observer placed in the connecting wire in such a manner that the current entering by his feet issues by his head, and that his face is always turned towards the needle, we shall see that in the above four positions the north pole is always deflected towards the left of the observer. By thus personifying the current, the different cases may be comprised in this general principle : *In the directive action of currents on magnets, the north pole is always deflected towards the left of the current.*

740. **Galvanometer or multiplier.**—The name *galvanometer*, or sometimes *multiplier* or *rheometer*, is given to a very delicate apparatus by which the existence, direction, and intensity of currents may be determined. It was invented by Schweigger in Germany a short time after Oersted's discovery.

In order to understand its principle, let us suppose a magnetic needle suspended by a filament of silk (fig. 592), and surrounded in the plane of the magnetic meridian by a copper wire, forming a complete circuit round the needle in the direction of its length. When this wire is traversed by a current, it follows, from what has been said in the previous paragraph, that in every part of the circuit an observer lying in the wire in the direction of the arrows, and looking at the needle *ab*, would have his left always turned towards the same point of the horizon, and consequently, that the action of the current in every part would tend to turn the north pole in the same direction : that is to say, that the actions of the four branches of the circuit concur to give the north pole the same direction. By coiling the copper wire in the direction of the needle, as represented in the figure, the action of the current has been *multiplied.* If instead of a single one, there are several circuits, provided they are insulated, the action becomes still more multiplied, and the deflection of the needle increases. Nevertheless, the action of the current cannot be multiplied indefinitely by increasing the number of windings, for, as we shall presently see, the intensity of a current diminishes as the length of the circuit is increased.

As the directive action of the earth continually tends to keep the needle in the magnetic meridian, and thus opposes the action of the current, the effect of the latter is increased by using an astatic system of two needles, as shown in fig. 593. The action of the earth on the needle is then very feeble, and, further, the actions of the current on the two needles become accumulated. In fact, the action of the circuit, from the direction of the current indicated by the arrows, tends to deflect the north pole of the lower needle towards the west. The upper needle, $a'b'$, is subjected to the action of two contrary currents mn and qp, but as the first is nearer, its action preponderates. Now this current passing below the needle, evidently tends to turn the pole a' towards the east, and, consequently, the pole b' towards the west : that is to say, in the same direction as the pole a of the other needle.

From these principles it will be easy to understand the theory of the *multiplier*. The apparatus represented in fig. 594 consists of a thick brass plate, D, resting on levelling screws ; on this is a rotatory plate, P, of the same metal, to which is fixed a copper frame, the breadth of which

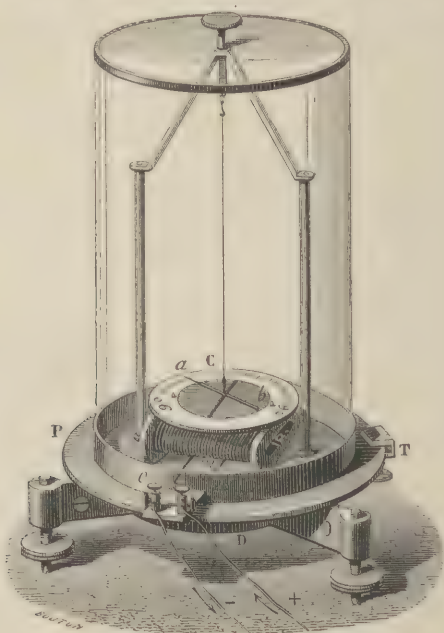


Fig. 594.

is almost equal to the length of the needles. On this is coiled a great number of turns of wire covered with silk. The two ends terminate in binding screws, i and o. Above the frame is a graduated circle, C, with a

central slit parallel to the direction in which the wire is coiled. The zero corresponds to the position of this slit, and there are two graduations on the scale, the one on the right and the other on the left of zero, but they only extend to 90°. By means of a very fine filament of silk, an astatic system is suspended; it consists of two needles, *ab* and *a'b'*, one above the scale, and the other within the circuit itself. These needles, which are joined together by a copper wire, like those in fig. 508 and fig. 595, and cannot move separately, must not have exactly the same magnetic intensity; for if they are exactly equal, every current, strong or weak, would always put them at right angles with itself.

In using this instrument, the diameter, to which corresponds the zero of the graduation, is brought into the magnetic meridian by turning the plate P until the end of the needle *ab* corresponds to zero. The instrument is fixed in this position by means of the screw clamp T.

The length and diameter of the wire vary with the purpose for which the galvanometer is intended. For one which is to be used in observing the currents due to chemical actions, a wire about $\frac{1}{6}$ millimeter in diameter, and making about 800 turns, is well adapted. Those for thermo-electric currents, which have low intensity, require a thicker and shorter wire, for example, thirty turns of a wire $\frac{2}{3}$ millimeter in diameter. For very delicate experiments, as in physiological investigations, galvanometers with as many as 30,000 turns have been used.

By means of a delicate galvanometer consisting of 2,000 or 3,000 turns of fine wire, the coils of which are carefully insulated by means of silk and shellac, currents of high intensity, as those of the electrical machine, may be shown. One end of the galvanometer is connected with the conductor and the other with the ground, and on working the machine the needle is deflected; affording thus an illustration of the identity of statical with dynamical electricity.

The deflection of the needle increases with the intensity of the current; the relation between the two is, however, so complex that it cannot well be deduced from theoretical considerations, but requires to be determined experimentally for each instrument. And in the majority of cases the instrument is used rather as a *galvanoscope* or *rheoscope*, that is, to ascertain the presence and direction of currents, than as a *galvanometer* or *rheometer* in the strict sense, that is, as a measurer of their intensity. The latter term *galvanometer* is, however, commonly used.

The *differential galvanometer* consists of a needle, as in an ordinary galvanometer, but round the frame of which are coiled two wires of the same kind and dimensions, carefully insulated from each other, and provided with suitable binding screws, so that separate currents can be passed through each of them. If the currents are of the same intensity but in different directions, no deflection is produced; where the needle is deflected one of the currents differs from the other. Hence the apparatus is used to ascertain a difference in intensity of two currents and to this circumstance owes its name.

741. **Sir W. Thomson's marine galvanometer.**—In laying submarine cables the want was felt of a galvanometer sufficiently sensitive to test

insulation, which at the same time was not affected by the pitching and rolling of the ship. For this purpose, Sir W. Thomson invented his marine galvanometer. Fig. 595 is from a drawing of this instrument kindly furnished by Messrs. Elliotts, by whom it is made. B represents a coil of many thousand turns of the finest copper wire, carefully insulated throughout, terminating in the binding screws EE. In the centre of this coil is a slide, which carries the magnet, the arrangement of which is represented on a larger scale in D. The magnet itself is made of a piece of fine watch spring about $\frac{3}{8}$ of an inch in length, and does not weigh more than a grain; it is attached to a small and very slightly concave mirror of very thin silvered glass. A single fibre of silk is stretched across the slide, and the mirror and magnet are attached to it in such a manner, that the fibre exactly passes through the centre of gravity in

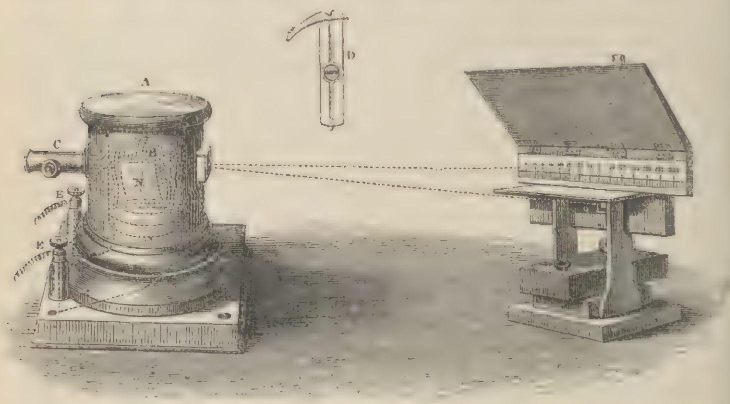


Fig. 595.

every position. As the mirror and magnet weigh only a few grains, they retain their position respecting the instrument, however the ship may pitch and roll. The slide fits in a groove in the coil, and the whole is enclosed within a wrought iron case with an aperture in front, and a wrought-iron lid on the top. The object of this is to counteract the influence of the terrestrial magnetism when the ship changes its course.

Underneath the coil is a large curved steel magnet N, which compensates the earth's directive action upon the magnet D; and in the side of the case, and on a level with D, a pair of magnets are placed with opposite poles together. By a screw suitably adjusted the poles of the magnets may be brought together; in which case they quite neutralise each other, and thus exert no action on the suspended magnet, or they may be slid apart from each other in such a manner that the action of either pole on D preponderates to any desired extent. This small magnet is then capable of very delicate adjustment. The large magnet N, and the pair

of magnets C, are analogous to the coarse and fine adjustment of a microscope.

At a distance of about three feet, there is a scale with the zero in the centre and the graduation extending on each side. Underneath this zero point is a narrow slit, through which passes the light of a paraffine lamp, and which traversing the window is reflected from the curved mirror against the graduated scale. By means of the adjusting magnets the image of the slit is made to fall on the centre of the graduation.

This being the case, if any arrangement for producing a current however weak be connected with the terminals, the spot of light is deflected either to one side or the other, according to the direction of the current; the stronger the current the greater the deflection of the spot; and if the current remains of constant strength for any length of time, the spot is stationary in a corresponding position.

The movement on a screen of a spot of light reflected from a body is the most delicate and convenient means of observing motions which of themselves are too small for direct measurement or observation. Hence this principle is frequently applied in experimental investigation and in lecture illustration. It is used in observing the motion of vibrating bodies (259), in measuring the variations of magnetism, in determining the expansion of solids, &c. &c.

It will be seen from the article on the Electric Telegraph, how alternate deflections of the spot of light may be utilised in forming a code of signals.

742. **Tangent compass, or tangent galvanometer.**—When a magnetic needle is suspended in the centre of a voltaic current in the plane of the

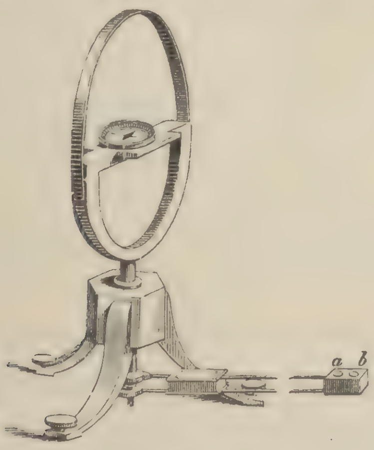


Fig. 596.

magnetic meridian, it can be proved that the intensity of a current is directly proportional to the tangent of the angle of deflection, provided the

dimensions of the needle are sufficiently small as compared with the diameter of the circuit. An instrument based on this principle is called the *tangent galvanometer*, or *tangent compass*. It consists of a copper ring, 12 inches in diameter, and about an inch in breadth, mounted vertically on a stand ; the lower half of the ring is generally fitted in a semicircular frame of wood to keep it steady. In the centre of the ring is suspended a delicate magnetic needle; in order to fulfil the conditions of the law its length must not exceed $\frac{1}{12}$ or $\frac{1}{10}$ of the diameter of the circle. Underneath the needle there is a graduated circle. The ends of the ring are prolonged in copper wires, fitted with mercury cups, *ab*, by which it can be connected with a battery or element. The circle is placed in the plane of the magnetic meridian, and the deflection of the needle is directly read off on the circle, and its corresponding value obtained from a table of tangents.

On account of its small resistance, the tangent compass is well adapted for currents of low tension, but in which a considerable quantity of electricity is set in motion. For currents which can overcome great resistance, but have only a small quantity of electricity, the multiplier is best fitted.

743. **Ohm's law.**—For a knowledge of the conditions which regulate he action of the voltaic current, science is indebted to the late Professor Ohm.

His results were at first deduced from theoretical considerations, but by his own researches as well as by those of Fechner, Pouillet, Daniell, De la Rive, Wheatstone, and others, they have received the fullest confirmation, and their great theoretical and practical importance has been fully established.

i. The force or cause by which electricity is set in motion in the voltaic circuit is called the *electromotive force*. The quantity of electricity which in any unit of time flows through a section of the circuit is called the *intensity of the current*. Ohm found that this intensity is the same in all parts of one and the same circuit however heterogeneous they were ; and also that it is proportional to the electromotive force.

It has further been found that when the same current is passed respectively through a short and through a long wire of the same material, its action on the magnetic needle is less in the latter case than in the former. Ohm accordingly supposed that in the latter case there was a greater *resistance* to the passage of the current than in the former ; and he proved that '*the resistance is inversely proportional to the intensity of the current*.'

On these principles Ohm founded the celebrated law which bears his name, that—

The intensity of the current is equal to the electromotive force divided by the resistance.

Which is expressed by the simple formula

$$I = \frac{E}{R},$$

where I is the intensity of the current, E the electromotive force, and R the resistance.

ii. The resistance of a conductor depends on three properties : its *conductivity*, which is a constant, determined for each conductor; its *section;* and its *length*. The resistance is obviously inversely proportional to the conductivity, that is, the less the conducting power the greater the resistance. This has been experimentally shown, and it has also been proved that *the resistance is inversely as the section and directly as the length of a conductor.* If then κ is the conductivity, ω the section, and λ the length of a conductor, we have

$$R = \frac{\lambda}{\kappa\omega} \text{ and } I = \frac{E}{\frac{\lambda}{\kappa\omega}} = \frac{\kappa\omega E}{\lambda},$$

that is, *the intensity of a current is inversely proportional to the length of the conductor and directly proportional to its section and conductivity.*

iii. In a voltaic battery composed of different elements, the intensity of the current is equal to the sum of the electromotive forces of all the elements divided by the sum of the resistances. Usually, however, a battery is composed of elements of the same kind, each having the same electromotive force and the same resistance.

In an ordinary element there are essentially two resistances to be considered : 1, That offered by the liquid conductor between the two plates, which is frequently called the *internal* or *essential resistance* ; and 2, That offered by the interpolar conductor which connects the two plates outside the liquid ; this conductor may consist either wholly of metal, or partly of metal and partly of liquids to be decomposed ; it is the *external* or *non-essential resistance.* Calling the former R and the latter r, Ohm's formula becomes

$$I = \frac{E}{R + r}.$$

iv. If any number, n, of similar elements are joined together, there is n times the electromotive force, but at the same time n times the internal resistance, and the formula becomes $\frac{nE}{nR + r}$. If the resistance in the interpolar, r, is very small, which is the case, for instance, when it is a short thick copper wire, it may be neglected in comparison with the internal resistance, and then we have

$$I = \frac{nE}{nR} = \frac{E}{R};$$

that is, a battery consisting of several elements produces in this case no greater effect than a single element. If, however, the external resistance r is very great, which is the case where the current has to pass through a long thin wire, or through a liquid, the intensity is within certain limits very nearly proportional to the number of elements.

v. If the plates of an element be made m times as large, there is no increase in the electromotive force, for this depends on the nature of the

metals and of the liquid, but the resistance is m times as small, for the section is m times larger; the expression becomes then

$$I = \frac{E}{\frac{R}{m} + r} = \frac{mE}{R + mr}.$$

Hence, an increase in the size of the plate, or, what is the same thing, a decrease in the internal resistance, does not increase the intensity to an indefinite extent; for ultimately the resistance of the element R vanishes in comparison with the resistance r, and the intensity always approximates to the value $I = \frac{E}{r}$.

In a thermo-electric pile, which consists of very short metallic conductors, the internal resistance R is very small. It may hence be neglected, and Ohm's formula becomes

$$I = \frac{E}{r};$$

that is, the intensity is inversely as the length of the connecting wire.

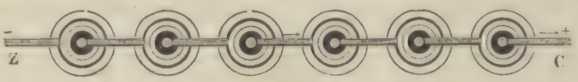


Fig. 597.

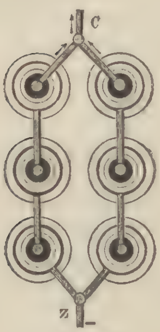


Fig. 598.

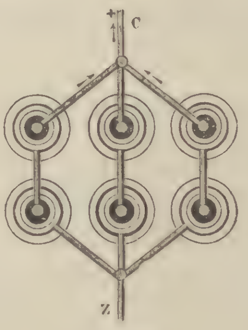


Fig. 599.

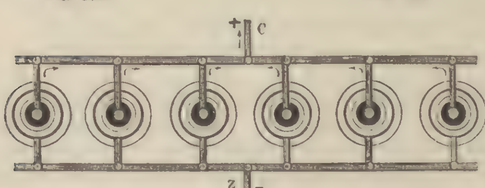


Fig. 600.

vi. Ohm's law enables us to arrange a battery so as to obtain the

greatest effect in any given case. For instance, with a battery of six elements there are the following four ways of arranging them: 1. In a single series (fig. 597), in which the zinc Z of one element is united with the copper C of the second; the zinc of this with the copper of the third, and so on; 2. Arranged in a system of three double elements, each element being formed by joining two of the former (fig. 598); 3. In a system of two elements, each of which consists of three of the original elements joined, so as to form one of triple the surface (fig. 599); 4. Lastly, of one large element, all the zincs and all the coppers being joined, so as to form a larger pair of six times the surface (fig. 600).

With a series of twelve elements there may be six different combinations, and so on for a larger number.

Now let us suppose that in the particular case of a battery of six elements the internal resistance R of each element is 3, and the external resistance $r = 12$. Then in the first case where there are six elements we have the value

$$I = \frac{6E}{6R + r} = \frac{6E}{6 \times 3 + 12} = \frac{6E}{30}.$$

If they were united so as to form three elements, each of double the surface, as the second case (fig. 598), the electromotive force then would be, the electromotive force in each element; there would also be a resistance R in each element, but this would only be half as great, for the section of the plate is now double; hence the intensity in this case would be

$$I' = \frac{3E}{\frac{3R}{2} + r} = \frac{3E}{\frac{9}{2} + 12} = \frac{6E}{33};$$

hence this change would lessen the intensity.

If with the same elements the resistance in the connecting wire were only $r = 2$, we should have the values in the two cases respectively—

$$I = \frac{6 \times E}{6 \times 3 + 2} = \frac{6E}{20},$$

$$\text{and } I' = \frac{3E}{\frac{3R}{2} + r} = \frac{6E}{9 + 4} = \frac{6E}{13}.$$

The result in this case is, therefore, more favourable. If the resistance r were 9 the intensity would be the same in both cases. Hence, by altering the size of the plates or the arrangement, favourable or unfavourable results are obtained according to the relation between R and r.

It can be shown that *in any given combination the maximum effect is obtained when the total resistance in the elements is equal to the resistance of the interpolar.* Suppose that in a given case n elements are arranged so as to form a battery of s couples, each consisting of t cells, $n = st$. Denoting the resistance of a single element by r, the total resistance of the battery thus arranged is $\frac{rs}{t}$. Now according to the above law the

maximum effect is obtained when $\frac{rs}{t}=l$, where l is the resistance of the interpolar. But $t=\frac{n}{s}$, hence $\frac{rs^2}{n}=l$, or $s=\sqrt{\frac{ln}{r}}$.

If in a given case we have 8 elements, each offering a resistance 15 and an interpolar with the resistance 40, we get $s=4{\cdot}3$. But this is an impossible arrangement, for it is not a whole number, and the nearest whole number must be taken. This is 4, and it will be found on making a calculation analogous to that above, that when arranged so as to form 4 elements, each of double surface, the greatest effect is obtained.

CHAPTER III.

EFFECTS OF THE CURRENT.

744. **Physiological actions.**—Under this name are included the effects produced by the battery on dead or living animals. They consist in very energetic shocks and muscular contractions when the batteries are powerful.

When the electrodes of a strong battery are held in the two hands a violent shock is felt, resembling that of a Leyden jar, especially if the hands are moistened with acidulated or saline water, which increases the conductivity. The shock is more violent in proportion to the number of elements used ; with a Bunsen's battery of 50 to 60 couples the shock is very strong, with 150 or 200 couples it is unbearable, and even dangerous when continued. It is less perceptible in the fore part of the arms than the shock of the Leyden jar, and when transmitted through a chain of several persons, it is generally only felt by those nearest the poles.

The shock, as in the case of the Leyden jar, is due to the recomposition of the two electricities ; with this difference, that with the Leyden jar the discharge being instantaneous, the resultant shock is so also ; while in the latter case, as the battery is immediately recharged after each discharge, the shocks succeed each other with rapidity. The action of the voltaic current on animals differs with its direction. Lehot and Marianini have shown that when the current is transmitted in one direction through the ramifications of the nerves, a muscular contraction is experienced when it commences, and a painful sensation when it ceases : whereas if it passes in the opposite direction through the nerves, pain is felt as long as it continues, and a contraction at the moment of its interruption. This difference of effects, however, is only produced in the case of feeble currents. With intense currents the contractions and the powerful effects take place both on closing and opening the current, whatever be its direction.

With a single couple no perceptible action is produced in the

fingers, but when it is applied to the tongue a peculiar effect is observed. The experiment may be made in a very simple manner. A piece of zinc as large as a sixpence is applied with its edge on the lower part of the tongue, and a sixpence is placed on the upper side; on bringing the two in contact a peculiar saline taste is perceived, which does not belong either to the silver or to the zinc, for it is only perceived when the plates touch, and disappears when they are separated.

By means of a powerful current, rabbits which have been suffocated half an hour have been restored to life; the head of a man who had been executed experienced such dreadful contractions that the spectators were horrified. The trunk, submitted also to the action of the current, partially raised itself, the hands were agitated, and struck adjacent objects, and the pectoral muscles imitated the respiratory movement. All vital actions were imperfectly reproduced, but ceased immediately with the cessation of the current.

745. **Thermal effects.**—When a voltaic current is passed through a metallic wire the same effects are produced as by the discharge of an electric battery; the wire becomes heated and even incandescent if it is very short and thin. With a powerful battery all metals are melted, even iridium and platinum, the least fusible of metals. Carbon is the only body which hitherto has not been fused by it. M. Despretz, however, with a battery composed of 600 Bunsen's elements joined in six series (743), has raised rods of very pure carbon to such a temperature that they were softened and could be welded together, indicating an incipient fusion.

A battery of 30 to 40 Bunsen's elements is sufficient to melt and volatilise fine wires of lead, tin, zinc, copper, gold, silver, iron, and even platinum, with differently coloured sparks. Iron and platinum burn with a brilliant white light; lead with a purple light; the light of tin and of gold is bluish white; the light of zinc is a mixture of white and gold; finally, copper and silver give a green light.

The thermal effects of the voltaic current are used for firing mines for military purposes and for blasting operations. The following arrangement devised by Major Schaw, is adopted in the English service. Fig. 601 represents a small wooden box provided with a lid. Two moderately stout copper wires, insulated by being covered with gutta-percha, are deprived of this coating at the ends, which are then passed through and through the box in the manner represented in the figure. The distance between them is $\frac{3}{8}$ of an inch, and a very fine platinum wire (one weighing 1·92 grains to the yard is the regulation size) is soldered across. The object of arranging the wires in this manner is that they shall not be in contact, and the strain which they exert may be spent on the box and not on the platinum wire joining them, which, being very thin, would be broken by a very slight pull. The box is then filled with fine-grained powder, and the lid tied down. The wires of the fuse are then carefully joined to the long conducting wires, which lead to the battery; these should be of copper, and as thick as is convenient, so as to offer very little resistance: No 16 gauge

copper wire is a suitable size. The fuse is then introduced into the charge to be fired : if it is for a submarine explosion the powder is contained in a

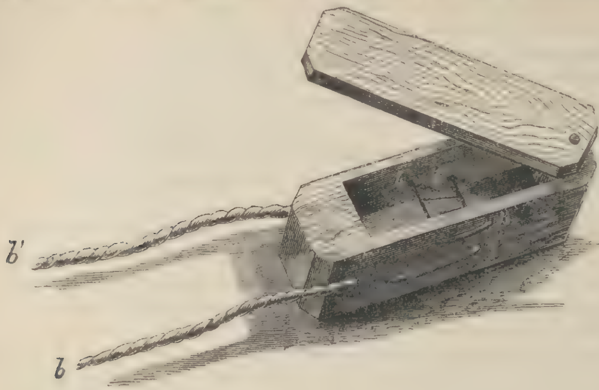


Fig. 601.

canister, the neck of which, after the introduction of the fuse, is carefully fastened by means of cement. When contact is made with the battery, which is effected through the intervention of mercury cups, the current traversing the platinum wire renders it incandescent, which fires the fuse ; and thus the ignition is communicated to the charge in which it is placed.

Although the thermal effects are most obvious in the case of thin wires, they are not limited to them ; with thicker wires they may be perceived by means of delicate thermometric arrangements, by which also the laws of the heating effect may be investigated.

Such an arrangement is called a *galvano-thermometer.* It consists essentially of a glass vessel containing alcohol, in which is a delicate thermometer ; the wire to be investigated is fitted to two platinum wires fused in the well-ground stopper of the vessel. The current is passed through the platinum wires, and its intensity measured by means of a tangent compass interposed in the circuit. By observing the increase of temperature in the thermometer in a given time, and knowing the weight of the alcohol, the mass of the wire, the specific heat, and the calorimetric values (389) of the vessel, and of the thermometer, compared with alcohol, the thermal effect which is produeed by the current in a given time can be calculated.

By apparatus of this kind the laws of the thermal effects have been investigated by Lenz, Joule, and Becquerel. They are as follows :

I. *The heat disengaged in a given time is directly proportional to the square of the intensity of the current, and to the resistance of the wire.*

II. *Whatever be the length of the wire, provided its diameter remains the same, and that the same quantity of electricity passes, the increase of temperature is the same in all parts of the wire.*

III. *For the same quantity of electricity, the increase of temperature in different parts of the wire is inversely as the fourth power of the diameter.*

If the current passes through a chain of platinum and silver wire of equal sizes, the platinum becomes more heated than the silver from its greater resistance ; and with a suitable current the platinum may become incandescent while the silver remains dark. This experiment was devised by Children. If a long thin platinum wire be raised to dull redness by passing a voltaic current through it, and if part of it be cooled down by ice, the resistance of the cooled part is diminished, the intensity of the current increases, and the rest of the wire becomes brighter than before.

If, on the contrary, a part of the feebly incandescent wire be heated by a spirit lamp, the resistance of the heated part increases, the intensity of the current diminishes, and the wire ceases to be incandescent in the non-heated part.

The cooling by the surrounding medium exercises an important influence on the phenomenon of ignition. A round wire is more heated by the same current than the same wire which has been beaten out flat ; for the latter with the same section offers a greater surface to the cooling medium than the others. For the same reason, when a wire is stretched in a glass tube on which two brass caps are fitted air-tight, and the wire is raised to dull incandescence by the passage of a current, the incandescence is more vivid when the air has been pumped out of the tube because it now simply loses heat by radiation, and not by communication to the surrounding medium.

Similarly, a current which will melt a wire in air will only raise it to dull redness in ether, and in oil or in water will not heat it to redness at all, for the liquids conduct heat away more readily than air does.

From the above laws it follows that the heating effect is the same in a wire whatever be its length, provided the current is constant ; but it must be remembered that by increasing the length of the wire we increase the resistance, and consequently diminish the intensity of the current ; further, in a long wire there is a greater surface, and hence more heat is lost by radiation and by conduction.

The thermal effect depends more on the size than on the number of the plates of a battery, for the resistance in the connecting wires is small. An iron wire may be melted by a single Wollaston's element, the zinc of which is 8 inches by 6. Hare's battery (725) has received its name *deflagrator* on account of its greater heating effect produced by the great surface of its plates.

When any circuit is closed a definite amount of heat is produced throughout the entire circuit ; and the amount of heat produced in any particular part of the circuit is greater, the greater the proportion which the resistance of this part bears to the entire circuit. Hence in firing mines the wire to be heated should be of as small section and of as small conductivity as are practical. These conditions are well satisfied by platinum, which has over iron the advantage of being less brittle and of not being liable to rust. Platinum too has a low specific heat, and is thus

raised to a higher temperature by the same amount of heat than a wire of greater specific heat.

On the other hand, the conducting wires should present as small a resistance as possible, a condition satisfied by a stout copper wire; and again, as the heating effect of any circuit is proportional to the square of the intensity, and as this is directly as the electromotive force, and inversely as the resistance, a battery with a high electromotive force, and small resistance, such as Grove's or Bunsen's, should be selected.

By means of a heated platinum wire, parts of the body may be safely cauterised which could not be got at by a red-hot iron; the removal of tumours may be effected by drawing a loop of platinum round their base, which is then gradually pulled together. It has been observed that when the temperature of the wire is about 600° C., the combustion of the tissues is so complete that there is no hæmorrhage; while at 1500° the action of the wire is like that of a sharp knife.

746. **Luminous effects.**—In closing a voltaic battery a spark is obtained at the point of contact, which is frequently of great brilliance. A similar spark is also perceived on breaking contact. These luminous effects are obtained when the battery is sufficiently powerful, by bringing the two electrodes very nearly in contact; a succession of bright sparks springs sometimes across the interval, which follow each other with such rapidity as to produce a continuous light. With eight or ten of Grove's elements brilliant luminous sparks are obtained by connecting one

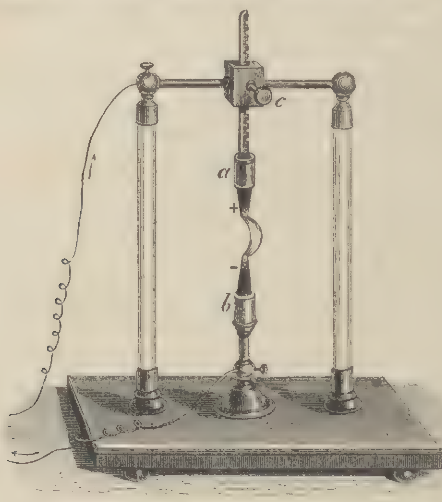


Fig. 602.

terminal of the battery with a file, and moving its point along the teeth of another file connected with the other terminal.

The most beautiful effect of the electric light is obtained when with the

terminals of the battery, two pencils of charcoal, are connected in the manner represented in fig. 602. The charcoal *b* is fixed, while the charcoal *a* can be raised and lowered by means of a rack and pinion motion *c*. The two charcoals being placed in contact the current passes, and their ends soon become incandescent. If they are then removed to a distance of about the tenth of an inch, according to the intensity of the current, a luminous arc extends between the two points, which has an exceedingly brilliant lustre, and is called the *voltaic arc*.

The length of this arc varies with the force of the current. In air it may exceed 2 inches with a battery of 600 elements, arranged in six series of 100 each, provided the positive pole is uppermost, as represented in the figure; if it is undermost, the arc is about one-third shorter. In vacuo the distance of the charcoal may be greater than in air; in fact, as the electricity meets with no resistance, it springs between the two charcoals, even before they are in contact. The voltaic arc can also be produced in liquids, but it is then much shorter, and its brilliancy is greatly diminished.

The voltaic arc has the property that it is attracted when a magnet is presented to it; a consequence of the action of magnets on currents.

Some physicists have considered the voltaic arc as formed of a very rapid succession of bright sparks. Its colour and shape depend on the nature of the conductors between which it is formed, and hence it is probable that it is due to the incandescent particles of the conductor, which are volatilised and transported in the direction of the current, that is, from the positive to the negative pole. The more easily the electrodes are disintegrated by the current, the greater is the distance at which the electrodes can be placed. Charcoal, which is a very friable substance, is one of the bodies which gives the largest luminous arc.

Recent researches by Edlund have shown that this disintegration of the terminals by the voltaic arc gives rise to an electromotive force opposed in direction to that of the main current.

Davy first made the experiment of the electric light, in 1801, by means of a battery of 2000 plates, each 4 inches square. He used charcoal points made of light wood charcoal which had been heated to redness, and immersed in a mercury bath; the mercury penetrating into the pores of the charcoal, increased its conductivity. When any substance was introduced into the voltaic arc produced by this battery, it became incandescent; platinum melted like wax in the flame of a candle; sapphire, magnesia, lime, and most refractory substances were fused. Fragments of diamond, of charcoal, and of graphite, rapidly disappeared without undergoing any previous fusion.

As charcoal rapidly burns in air, it was necessary to operate in vacuo, and hence the experiment was for a long time made by fitting the two points in an electric egg, like that represented in fig. 566. At present the electrodes are made of gas graphite, a modification of charcoal deposited in gas retorts; this is hard and compact, and only burns slowly in air: hence it is unnecessary to operate in vacuo. When the experiment is made in vacuo, there is no combustion, but the charcoal wears away at

the positive pole, while it is somewhat increased on the negative pole, indicating that there is a transport of solid matter from the positive to the negative pole.

747. **Foucault's experiment.**—This consists in projecting on a screen the image of the charcoal points produced in the camera obscura at the moment at which the electric light is formed (fig. 603). By means of this

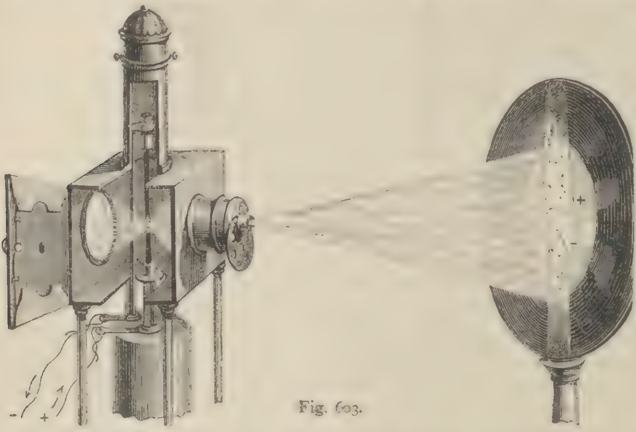


Fig. 603.

experiment, which is made by the photo-electric microscope already described (fig. 441), the two charcoals can be readily distinguished, and the positive charcoal is seen to become somewhat hollow and diminish, while the other increases. The globules represented on the two charcoals arise from the fusion of a small quantity of silica contained in the charcoal. When the current begins to pass, the negative charcoal first becomes luminous, but the light of the positive charcoal is the brightest; as it also wears away the most rapidly, it ought to be rather the larger.

748. **Regulator of the electric light.**—When the electric light is to be used for illumination, it must be as continuous as other modes of lighting. For this purpose, not only must the current be constant, but the distance of the charcoals must not alter, which necessitates the use of some arrangement for bringing them nearer together in proportion as they wear away. One of the best modes of effecting this is by an apparatus invented by M. Duboscq.

In this regulator the two charcoals are moveable, but with unequal velocities, which are virtually proportional to their waste. The motion is transmitted by a drum placed on the axis, *xy* (fig. 604). This turns in the direction of the arrows two wheels, *a* and *b*, the diameters of which are as 1 : 2, and which respectively transmit their motion to two rack-works, C′ and C. C lowers the positive charcoal, *p*, by means of a rod sliding in the tube, H, while the other C′ raises the negative charcoal, *n*, half as rapidly. By means of the milled head, *y*, the drum can be wound up, and at the same time the positive charcoal moved by the hand; the

milled head, x, moves the negative charcoal also by the hand, and independently of the first. For this purpose the axis, xy, consists of two parts pressing against each other with some force, so that holding the milled head, x, between the fingers, the other, y, may be moved, and by

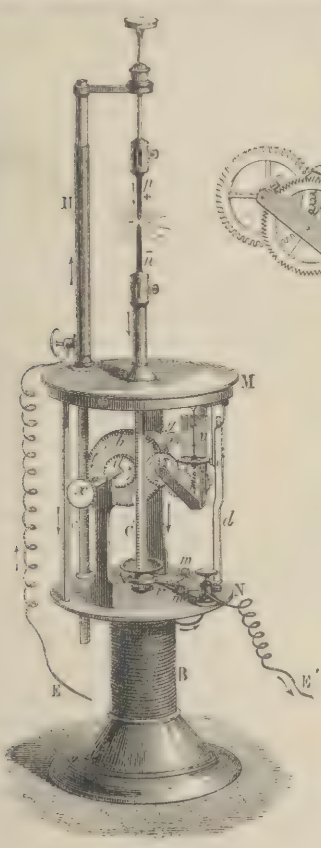


Fig. 604.

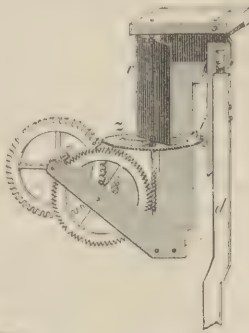


Fig. 605.

holding the latter the former can be moved. But the friction is sufficient when the drum works to move the two wheels a and b and the two rack works.

The two charcoals being placed in contact, the current of a powerful battery of 40 to 50 elements reaches the apparatus by means of the wires, E and E′. The current rising in H descends by the positive charcoal, then by the negative charcoal, and reaches the apparatus, but without passing into the rackwork, C, or into the part on the right of the plate, N ; these pieces being insulated by ivory discs placed at their lower part.

The current ultimately reaches the bobbin B, which forms the foot of the regulator, and passes into the wire, E′. Inside the bobbin is a bar of soft iron, which is magnetised as long as the current passes in the bobbin, and demagnetised when it does not pass, and this temporary magnet is the regulator. For this purpose it acts attractively on an armature of soft iron, A, open in the centre so as to allow the rackwork C′ to pass, and fixed at the end of a lever, which works on two points, *mm*, and transmits a slight oscillation to a rod, *d*, which, by means of a catch, *i*. seizes the wheel *z*, as is seen on a larger scale in figure 605. By an endless screw, and a series of toothed wheels, the stop is transmitted to the drum, and the rackwork being fixed, the same is the case with the carbons. This is what takes place so long as the magnetisation in the bobbin is strong enough to keep down the armature, A: but in proportion as the carbons wear away, the current becomes feebler, though the voltaic arc continues, so that ultimately the attraction of the magnet no longer counterbalances a spring, *r*, which continually tends to raise the armature. It then ascends, the piece *d* disengages the stop *i*, the drum works, and the carbons come nearer ; they do not, however, touch, because the intensity of the current gains the upper hand, the armature A is attracted, and the carbons remain fixed. As their distance only varies within very narrow limits, a regular and continuous light is obtained with this apparatus until the carbons are quite used.

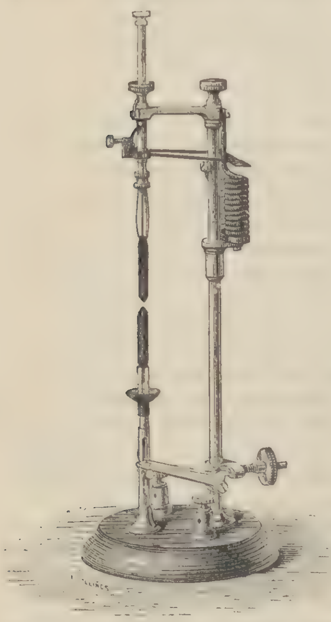


Fig. 606.

By means of this regulator, M. Duboscq illuminates the photogenic apparatus represented fig. 441, by which all the optical experiments may be performed for which solar light was formerly necessary.

749. **Browning's regulator.**—A much simpler apparatus, represented in fig. 606, has been devised by Mr. John Browning. It has the great advantage of being less costly than the other lamps, and also of requiring a smaller number of elements to work it. The current enters the lamp by a wire attached to a binding screw on the base of the instrument, passing up the pillar by the small electromagnet to the centre pillar along the top of the horizontal bar, down the left hand bar through the two carbons, and away by a wire attached to a binding screw on the left hand. A tube holding the upper carbon slides

freely up and down a tube at the end of the cross-piece, and would by its own weight rest on the lower carbon, but the electromagnet has a keeper to which is attached a rest that encircles the carbon tube and grasps it. When the electromagnet works and attracts the keeper, the rest tightens and prevents the descent of the carbon. When the keeper is not attracted the rest loosens, and the carbon holder descends.

When the two carbons are at rest, on making contact with a battery the current traverses both carbons and no light is produced. But if the upper carbon be raised ever so little a brilliant light is emitted. When the lamp is thus once set to work the rod attached to the upper carbon may be let go, and the magnet will afterwards keep the lamp at work. For when some of the carbon is consumed, and the interval between the two is too great for the current to pass, the magnet loses some of its power, the keeper loosens its hold on the carbon, and this descends by its own weight. When they are sufficiently near, but before they are in contact, the current is reestablished ; the magnet again draws on the keeper and the keeper again checks the descent of the carbon and so forth. Thus the points are retained at the right distances apart, and the light is continuous and brilliant.

750. **Properties and intensity of the electric light.**—The electric light has similar chemical properties to solar light ; it effects the combination of chlorine and hydrogen, acts chemically on chloride of silver, and applied to photography gives fine impressions, remarkable for the warmth of its tones ; it is, however, inapplicable for taking portraits, as it fatigues the sight too greatly.

Passed through a prism, the electric light, like the sun, is decomposed and gives a spectrum. Wollaston, and more especially Fraunhofer, have found that the spectrum of the electric light differs from that of other lights and of the sun-light by the presence of several very bright lines, as has been already stated. Wheatstone was the first to observe that by using electrodes of different metals, the spectrum and the lines are modified. According to Despretz the bright lines are fixed, and independent of the intensity of the current.

Masson has recently studied the electric light in great detail, and has experimented upon the light of the electric machine, that of the voltaic arc, and that of Ruhmkorff's coil. He has found the same colours in the electric spectrum as in the solar spectrum, but traversed by very brilliant luminous bands of the same shade as that of the colour in which they occur. The number and position of these bands do not depend on the intensity of the light, but, as we have seen, upon the substances between which the voltaic arc is formed.

With carbon the lines are remarkable for their number and brilliancy ; with zinc the spectrum is characterised by a very marked apple-green tint ; silver produces a very intense green ; with lead a violet tint predominates, and so on with other metals.

Bunsen, in experimenting with 48 couples, and removing the charcoals to a distance of a quarter of an inch, has found that the intensity of the electric light is equal to that of 572 candles.

Fizeau and Foucault have compared the chemical effects of the solar and the electric lights, by investigating their action on iodized silver plates. Representing the intensity of the sun-light at midday at 1000, these physicists found that that of 46 Bunsen's elements was 235, while that of 80 elements was only 238. It follows that the intensity does not increase to any material extent with the number of the couples; but experiment shows that it increases considerably with their surface. For with a battery of 46 elements, each consisting of 3 elements, with their zinc and copper respectively united so as to form one element of triple surface (743), the intensity was 385, the battery working for an hour; that is to say, more than a third of the intensity of the solar light.

Despretz observes that too great precautions cannot be taken against the effects of the electric light when they attain a certain intensity. The light of 100 couples, he says, may produce very painful affections of the eyes. With 600, a single moment's exposure to the light is sufficient to produce very violent headaches and pains in the eye, and the whole frame is affected as by a powerful sunstroke.

Mr. Way has obtained a very bright light by passing the electric current along a stream of mercury. The light is produced by the incandescence of the mercury vapour; it has a somewhat flickering character, and a greenish tinge.

Attempts have been made to apply the electric light to the illumination of rooms, and even of streets; but partly the cost, and partly the difficulty of producing with it a uniform illumination, inasmuch as the shadows are thrown into too sharp relief, have hitherto been great obstacles to its use. Yet it is advantageously applied in special cases, such as the photo-electric microscope, illuminations in theatres, etc.

751. **Mechanical effects of the battery.**—Under this head may be included the motion of solids and liquids effected by the current. An example of the former is found in the voltaic arc, in which there is a passage of the molecules of carbon from the positive to the negative pole (746).

To the mechanical effects of the battery some physicists have referred the following experiment, due to Porret. Having divided a glass vessel into two compartments by a porous diaphragm consisting of bladder, he poured water into the two compartments to the same height, and immersed two electrodes of platinum in connection with a battery of 80 elements. As the water became decomposed, part of the liquid was carried in the direction of the current, through the diaphragm, from the positive to the negative compartment, where the level rose above that in the other compartment. A solution of blue vitriol is best for these experiments, because then the disturbing influence of the disengagement of gas at the negative electrode is avoided.

The pressure with which the liquid is urged forwards is nearly directly proportional to the intensity of the current, the magnitude of the surface on which the liquid moistens the sides, and to the resistance, and is nearly inversely proportional to the section of the liquid in the porous diaphragm.

Conversely when a liquid is forced through a diaphragm by mechanical means electrical currents are produced if on both sides the diaphragm metal electrodes of the same material are immersed in the liquid in conducting communication with each other.

According to Wertheim, the elasticity of metallic wires is diminished by the current, and not by the heat alone, but by the electricity : he has also found that the cohesion is diminished by the passage of a current.

To the mechanical effects of the current may be assigned the sounds produced in soft iron when submitted to the magnetic action of a discontinuous current ; a phenomenon which will be subsequently described.

752. **Chemical effects.**—These are among the most important of all the actions, either of the simple or compound circuit. The first decomposition effected by the battery was that of water, obtained in 1800 by Carlisle and Nicholson by means of a voltaic pile. Water is rapidly decomposed by 4 or 5 Bunsen's cells ; the apparatus (fig. 607) is very convenient for the purpose. It consists of a glass vessel fixed on a wooden base. In the bottom of the vessel two platinum electrodes, *p* and *n*, are fitted, communicating by means of copper wires with the binding screws. The vessel is filled with water to which some sulphuric acid has been added to increase its conductivity, for pure water is a very imperfect conductor ; two glass tubes filled with water are inverted over the electrodes, and on interposing the apparatus in the circuit of a battery decomposition is rapidly set up, and gas bubbles rise from the surface of each pole. The volume of gas liberated at the negative pole is about double that at the positive, and on examination the former gas is found to be hydrogen and the latter gas oxygen. This experiment accordingly gives at once the qualitative and quantitative analysis of water. The oxygen thus obtained has the peculiar and penetrating odour observed when an electrical machine is worked (715), and which is due to ozone. The water contained at the same time some peroxide of hydrogen, in producing which some oxygen is consumed. Owing to these two causes the volume of oxygen is less than that required by the composition of water, which is two volumes of hydrogen to one of oxygen.

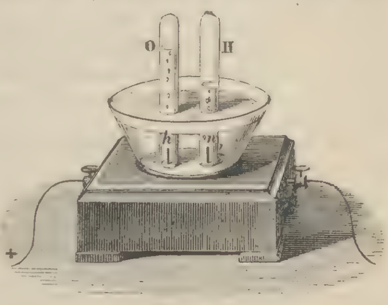


Fig. 607.

753. **Electrolysis.**—To those substances which, like water, are resolved into their elements by the voltaic current, the term *electrolyte* has been applied by Faraday, to whom the principal discoveries in this subject and the nomenclature are due. *Electrolysis* is the decomposition by the voltaic battery ; the positive electrode was by Faraday called the

anode, and the negative electrode the *kathode*. The products of decomposition are *iones; katione*, that which appears at the kathode; and *anione*, that which appears at the anode.

By means of the battery, the compound nature of several substances which had previously been considered as elements has been determined. By means of a battery of 250 couples, Davy, shortly after the discovery of the decomposition of water, succeeded in decomposing the alkalies potass and soda, and proved that they were the oxides of the hitherto unknown metals potassium and sodium. The decomposition of potass may be demonstrated with the aid of the battery of 4 to 6 elements in the following manner: a small cavity is made in a piece of solid caustic potass, which is moistened, and a drop of mercury placed in it. The potass is placed on a piece of platinum connected with the positive pole of the battery. The mercury is then touched with the negative pole. When the current passes, the potass is decomposed, oxygen is liberated at the positive pole, while the potassium liberated at the negative pole amalgamates with the mercury. On distilling this amalgam out of contact with air, the mercury passes off, leaving the potassium.

The decomposition of binary compounds, that is, bodies containing two elements, is quite analogous to that of water and of potass; one of the elements goes to the positive, and the other to the negative pole. The bodies separated at the positive pole are called *electronegative* elements, because at the moment of separation they are considered to be charged with negative electricity, while those separated at the negative pole are called *electropositive* elements. One and the same body may be electronegative or electropositive, according to the body with which it is associated. For instance, sulphur is electronegative towards hydrogen, but is electropositive towards oxygen. The various elements may be arranged in such a series that any one in combination is electronegative to any following, but electropositive towards all preceding ones. This is called the *electro-chemical series*, and begins with oxygen as the most electronegative element, terminating with potassium as the most electropositive.

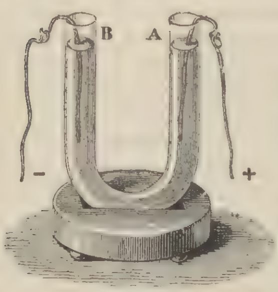


Fig. 608.

The decomposition of hydrochloric acid into its constituents, chloride and hydrogen, may be shown by means of the apparatus represented in fig. 608. Carbon electrodes must, however, be substituted for those of platinum, which is attacked by the liberated chlorine; a quantity of salt also must be added to the hydrochloric acid, in order to diminish the solubility of the liberated chlorine. The decomposition of iodide of potassium may be demonstrated by means of a single element. For this purpose a piece of bibulous paper is soaked with a solution of starch, to which iodide of potassium is added. On touching this paper with the

electrodes a blue spot is produced at the positive pole, due to the action of the liberated iodine on the starch.

754. **Decomposition of salts.**—Ternary salts in solution are decomposed by the battery, and then present effects varying with the chemical affinities, and the intensity of the current. In all cases the acid, or the body which is chemically equivalent to it, is electronegative in its action towards the other constituent. The decomposition of salts may be readily shown by means of the bent tube represented in fig. 549. This is nearly filled with a saturated solution of a salt, say sulphate of sodium, coloured with tincture of violets. The platinum electrodes of a battery of four Bunsen's elements are then placed in the two legs of the tube. After a few minutes the liquid in the positive leg, A, becomes of a red, and that in the negative leg, B, of a green colour, showing that the salt has been resolved into acid which has passed to the positive, and into a base which has gone to the negative pole, for these are the effects which a free acid and a free base respectively produce on tincture of violets.

In a solution of sulphate of copper, free acid and oxygen gas appear at the positive electrode, and metallic copper is deposited at the negative electrode. In like manner, with nitrate of silver, metallic silver is deposited on the negative, while free acid and oxygen appear at the positive electrode.

This decomposition of salts was formerly explained by saying that *the acid was liberated at the positive electrode and the base at the negative.* Thus sulphate of potassium, K_2OSO_3, was considered to be resolved into sulphuric acid, SO_3, and potash, K_2O. This view regarded salts composed of three elements as different in their constitution from binary or haloid salts. Their electrolytic deportment has led to a mode of regarding the constitution of salts, which brings all classes of them under one category. In sulphate of potassium, for instance, the electropositive element is potassium, while the electronegative element is a complex of sulphur and oxygen, which is regarded as a single group, SO_4, and to which the name *oxy-sulphion* may be assigned. The formula of sulphate of potassium would thus be K_2SO_4, and its decomposition would be quite analogous to that of chloride of potassium, KCl, chloride of lead, $PbCl_2$, iodide of potassium, KI. The electronegative group SO_4 corresponds to a molecule of chlorine or iodine. In the decomposition of sulphate of potassium the potassium liberated at the negative pole decomposes water, forming potash and liberating hydrogen. In like manner the electronegative constituent SO_4, which cannot exist in the free state, decomposes into oxygen gas, which is liberated, and into anhydrous sulphuric acid, SO_3, which immediately combines with water to form ordinary sulphuric acid H_2SO_4. In fact, where the action of the battery is strong these gases are liberated at the corresponding poles; in other cases they combine in the liquid itself, reproducing water. The constitution of sulphate of copper, $CuSO_4$, and of nitrate of silver, $AgNO_3$, and their decomposition, will be readily understood from these examples.

755. **Transmissions effected by the current.**—In chemical decompositions effected by the battery there is not merely a separation of the

elements, but a passage of the one to the positive, and of the other to the negative electrode. This phenomenon has been demonstrated by Davy by means of several experiments, of which the two following are examples :—

i. He placed solution of sulphate of sodium in two capsules connected by a thread of asbestos moistened with the same solution, and immersed the positive electrode in one of the capsules, and the negative electrode in the other. The salt was decomposed, and at the expiration of some time all the sulphuric acid was found in the first capsule, and the soda in the second.

ii. Having taken three glasses, A, B, and C, he poured into the first, solution of sulphate of sodium, into the second, dilute syrup of violets, and into the third pure water, and connected them by moistened threads of asbestos. The current was then passed in the direction from C to A. The sulphate in the vessel A was decomposed, and in the course of time there was nothing but soda in this glass which formed the negative end, while all the acid had been transported to the glass C, which was positive. If, on the contrary, the currents passed from A to C, the soda was found in C, while all the acid remained in A, but in both cases the remarkable phenomenon was seen that the syrup of violets in B neither became red nor green by the passage of the acid or base through its mass, a phenomenon the explanation of which is based on the hypothesis enunciated in the following paragraph.

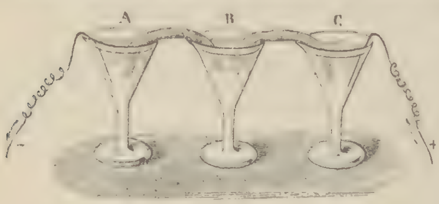


Fig. 609.

756. **Grotthüss's hypothesis.**—Grotthüss has given the following explanation of the chemical decompositions effected by the battery. Adopting the hypothesis that in every binary compound or body which acts as such, one of the elements is electropositive, and the other electronegative, he assumes that under the influence of the contrary electricities of the electrodes, there is effected in the liquid in which they are immersed, a series of successive decompositions and recompositions from one pole to the other. Hence it is only the elements of the terminal molecules which do not recombine, and remaining free appear at the electrodes. Water, for instance, is formed of one atom of oxygen and two atoms of hydrogen, the first gas being electronegative, and the second electropositive. Hence when the liquid is traversed by a sufficiently powerful current, the molecule *a* in contact with the positive pole arranges itself as shown in fig. 551, that is, the oxygen is attracted and the hydrogen repelled. The oxygen of this molecule is then given off at the positive electrode, the liberated

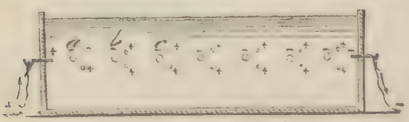


Fig. 610.

hydrogen immediately unites with the oxygen of the molecule *b*, the hydrogen of this with the oxygen of the molecule *c*, and so on, to the negative electrode, where the last atoms of hydrogen become free and appear on the poles. The same theory applies to the metallic oxides, to the acids and salts, and explains why in the experiment mentioned in the preceding paragraph, the syrup of violets in the vessel B becomes neither red nor green. The reason why, in the fundamental experiment, the hydrogen is given off at the negative pole when the circuit is closed will be readily understood from a consideration of this hypothesis.

757. **Laws of electrolysis.**—The laws of electrolysis were discovered by Faraday; the most important of them are as follows:—

I. *Electrolysis cannot take place unless the electrolyte is a conductor.* Hence ice is not decomposed by the battery, because it is a bad conductor. Other bodies, such as oxide of lead, chloride of silver, etc., are only electrolysed in a fused state, that is, when they can conduct the current.

II. *The energy of the electrolytic action of the current is the same in all its parts.*

III. *The same quantity of electricity—that is, the same electric current—decomposes chemically equivalent quantities of all the bodies which it traverses*; from which it follows, *that the weights of elements separated in these electrolytes are to each other as their chemical equivalents.*

If an apparatus for decomposing water (fig. 607) and various U-shaped tubes containing respectively fused oxide of lead and chloride of tin are interposed in the same voltaic current, which must be sufficiently powerful, these substances will be decomposed; the electronegative elements will be separated at the positive, and the electropositive at the negative poles. The quantities of substances liberated are in a certain definite relation. Thus for every 18 parts of water decomposed in the voltameter there will be liberated 2 parts of hydrogen, 207 parts of lead, and 117 of tin at the respective negative electrodes, and 16 parts of oxygen, and 71 (or $2 \times 35 \cdot 5$) parts of chlorine at the corresponding positive electrode. Now these numbers are exactly as the equivalents (not as the atomic weights) of the bodies.

It will further be found, that in each of the cells of the battery 65 parts by weight of zinc have been dissolved, for every two parts by weight of hydrogen liberated; that is, that for every equivalent of a substance decomposed in the circuit one equivalent of zinc is dissolved. This is the case whatever be the number of cells. An increase in the number only has the effect of overcoming the great resistance which many electrolytes offer, and of accelerating the decomposition. It does not increase the quantity of the electrolyte decomposed.

IV. It follows from the above law, that *the quantity of a body decomposed in a given time is proportional to the intensity of the current.* On this is founded the use of Faraday's *voltameter*, in which the intensity of a current is ascertained from the quantity of water which it decomposes in a given time. It consists of a glass vessel, in which two platinum electrodes are fixed. In the neck of a vessel a bent delivery tube is fitted, and the mixed gases are collected in a graduated cylinder, so that

their volume can be determined, which, reduced to a constant temperature and pressure, is a measure of their quantity.

The use of this voltameter appears simple and convenient; and hence some physicists have proposed as unit of the intensity of the current, that intensity which in one minute yields a cubic centimeter of mixed gas reduced to the temperature 0° and the pressure 760 mm. But there are several objections to the use of the voltameter. In the first place it does not indicate the intensity at any given moment, for in order to obtain measurable quantities of gas the current must be continued some time. Again the voltameter gives no indications of the changes which take place in this time, but only shows the mean intensity. Moreover the voltameter itself offers a very considerable resistance, and can only be used in the case of strong currents; for feeble currents either do not decompose water, or only yield quantities of gas too small for accurate measurement. In addition to this the indications of the voltameter depend not only on the intensity of the current, but on the acidity of the water, and the distance and size of the electrodes.

The *silver voltameter* is an instrument for measuring the intensity of the current. A solution of nitrate of silver of known strength is placed in a platinum dish which is connected with the negative pole; in this solution is placed the positive pole, which consists of a rod of silver wrapped round with muslin.

The silver which separates at the negative pole is washed, dried, and weighed; and the weight thus produced in a given time is a measure for the intensity of the current. The silver particles which become detached from the positive pole are retained in the muslin.

The current from the electrical machine, which is of very high intensity, is capable of traversing any electrolyte, but the quantity which it can decompose is extremely small as compared even with the smallest voltaic apparatus, and it must be concluded that the quantity developed by the frictional machine is very small as compared with that developed by chemical action.

It has been calculated by Weber, that if the quantity of positive electricity required to decompose a grain of water were accumulated on a cloud at a distance of 3,000 feet from the earth's surface, it would exert an attractive force upon the earth of upwards of 1,500 tons.

758. **Polarisation.**—When the platinum electrodes, which have been used in decomposing water, are disconnected from the battery, and connected with a galvanometer, the existence of a current is indicated which has the opposite direction to that which had previously passed. This phenomenon is explained by the fact that oxygen has been condensed on the surface of the positive plate, and hydrogen on the surface of the negative plate, analogous to what has been already seen in the case of the nonconstant batteries (726). The effect of this is to produce two different electrometers, which produce a current opposed in direction to the original one, and which, therefore, must weaken it.

On this principle batteries may be constructed of pieces of metal of the same kind—for instance platiumn—which otherwise give no current. A

piece of moistened cloth is interposed between each pair, and each end of this system is connected with the poles of a battery. After some time the apparatus has received a charge, and if separated from the battery can itself produce all the effects of a voltaic battery. Such batteries are called *secondary* batteries. Their action depends on an alteration of the surface of the metal produced by the electric current; the constituents of the liquid with which the cloth is moistened having become accumulated on the opposite plates of the circuit.

A dry pile which has become inactive may be used as a secondary battery. When a current is passed through it, in a direction contrary to that which the active battery yields, it then regains its activity.

759. **Grove's gas battery.**—On the property which metals have, of condensing gases on their surfaces, Grove has constructed his gas battery. In its simplest form it consists of two glass tubes, in each of which is fused a platinum electrode, provided on the outside with binding screws. In order to give greater efficiency these electrodes are covered with finely divided platinum. One of the tubes is partially filled with hydrogen, and the other partially with oxygen, and they are inverted over dilute sulphuric acid, so that half the platinum is in the liquid and half in gas. On connecting the electrodes with a galvanometer the existence of a current is indicated, whose direction in the connecting wire is from the platinum in oxygen to that in hydrogen; so that the latter is negative towards the former. As the current passes through water this is decomposed; oxygen is separated at the positive plate, and hydrogen at the other. These gases unite with the gases condensed on their surface, so that the volume of gas in the tubes gradually diminishes, but in the ratio of one volume of oxygen to two volumes of hydrogen. These elements can be formed into a battery by joining the dissimilar plates with one another just as they are joined in an ordinary battery. One element of such a battery is sufficient to decompose iodide of potassium, and four will decompose water.

760. **Passive state of iron.**—With polarisation is probably connected a very remarkable chemical phenomenon, which many metals exhibit, but more especially iron. When this is placed in contact with platinum wire and immersed in concentrated nitric acid it is unattacked, while the iron alone would be dissolved by the acid. This condition of iron is called the *passive state*, and upon it depends the possibility of the zinc-iron battery (730). It is probable that in the above experiment a thin superficial layer of sesquioxide of iron is formed, which is then negative towards platinum.

761. **Nobili's rings.**—When a drop of acetate of copper is placed on a silver plate, and the silver touched in the middle of the drop with a piece of zinc, there are formed around the point of contact a series of copper rings alternately dark and light. These are *Nobili's coloured rings.* They may be obtained in beautiful iridescent colours by the following process: A solution of oxide of lead in potash is obtained by boiling finely powdered litharge in a solution of potash. In this solution is immersed a polished plate of silver or of German silver, which is connected

with the positive electrode of a battery of eight Bunsen's elements. With the negative pole is connected a fine platinum wire fused in glass, so that only its point projects; and this is placed in the liquid at a small distance from the plate. Around this point binoxide of lead is separated on the plate in very thin concentric layers, the thickness of which decreases from the middle. They show the same series of colours as Newton's coloured rings in transmitted light. The binoxide of lead owes its origin to a secondary decomposition ; by the passage of the current some oxide of lead is decomposed into lead, which is deposited at the negative pole, and oxygen which is liberated at the positive, and this oxygen combines with some oxide of lead to form binoxide, which is deposited on the positive pole as the decomposition proceeds.

762. **Arbor Saturni or lead tree. Arbor Dianæ.**—When, in a solution of a salt, is immersed a metal which is more oxidisable than the metal of the salt, the latter is precipitated by the former, while the immersed metal is substituted equivalent for equivalent for the metal of the salt. This precipitation of one metal by another is partly attributable to the affinities, and partly to the action of a current which is set up as soon as a portion of the less oxidisable metal has been deposited. The action is promoted by the presence of excess of acid in the solution.

A remarkable instance of the precipitation of one metal by another is the *arbor Saturni*. This name is given to a series of brilliant ramifications obtained by zinc in solutions of acetate of lead. A glass flask is filled with a clear solution of this salt, and the vessel closed with a cork, to which is fixed a piece of zinc in contact with some brass wires. The flask being closed is left to itself. At the expiration of a few days brilliant lammæ of metallic lead are deposited on the brass wires, closely resembling vegetation, from which the old alchemical name is derived. For the same reason the name *arbor Dianæ* has been given to the metallic deposit produced in a similar manner by mercury in a solution of nitrate of silver.

ELECTROMETALLURGY.

763. **Electrometallurgy.**—The decomposition of salts by the battery has received a most important application in *electrometallurgy*, or the art of precipitating metals from their solutions by the slow action of a galvanic current. This art was discovered independently by Spencer in England, and by Jacobi in Petersburgh.

In order to reproduce a medal or any other object by this process a hollow cast must first be made, on which is deposited the metallic layer, which reproduces the medal in relief. If the medal is of metal the simplest way to form the cast is to use a fusible alloy, which may consist of 5 parts of lead, 8 of bismuth, and 3 of tin. Some of the melted alloy is poured into a shallow box, and just as it begins to solidify the medal is placed horizontally on it in a fixed position. When the alloy has become cool a slight shock is sufficient to detach the medal. A copper wire is then bound round the edge of the mould, by which it can be con-

nected with the negative electrode of the battery, and then the edge and the posterior surface are covered with a thin non-conducting layer of wax, so that the deposit is only formed on the mould itself.

In order to take a copper cast, a bath is filled with saturated solution of sulphate of copper and two copper rods, B and D, stretched across (fig. 611): one connected with the negative and the other with the

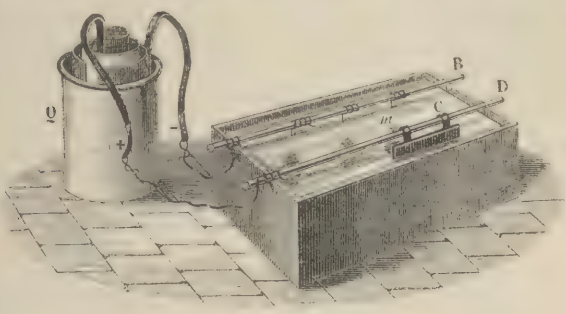


Fig. 611.

positive pole of a Grove's, or preferably, from its greater constancy, a Daniell's element. From the rod connected with the negative pole is suspended the mould *m*, and from the other a plate of copper, C. The current being thus closed, the sulphate of copper is decomposed, acid is liberated at the positive pole, while copper is deposited at the negative pole, on the mould suspended from the rod, B, to which indeed several moulds may be attached. At the expiration of 48 hours the mould is covered with a non-adherent, solid, resisting layer of copper. In order completely to avoid adherence the mould ought previously to immersion to be brushed with a fine brush passed very lightly over a fatty body, or rapidly passed through a smoky flame, so as to form a very slight deposit of solid matter.

If the cast to be reproduced is of plaster, an alloy cannot be used. It must first be immersed in a bath of melted stearine, and withdrawn quickly; when withdrawn it dries almost immediately, which arises from a penetration of stearine into the pores of the plaster. When cooled it is coated with graphite, or black lead, which is rubbed with a brush; a band of cartridge paper is then affixed round the edge, and some plaster or melted stearine is poured upon it; on cooling this gives a hollow cast of the original medal. This is prevented from adhering to the plaster by the layer of graphite; it is removed and covered with graphite in order to make it conduct. The mould thus prepared is suspended, as in the previous case, from the negative pole of the battery.

Gutta-percha also gives very sharp moulds. The object of which the cast is to be taken is coated with a layer of graphite to prevent adherence, and then a quantity of gutta-percha having been placed in hot water until it is quite soft, is pressed against the object to be copied. On detaching

the gutta-percha a very faithful hollow cast of the object is obtained. This cast is covered with graphite in order to make it conduct ; being connected with the negative pole it is then suspended in a concentrated solution of sulphate of copper, and in about 48 hours a copper copy of the original object is obtained.

The copper plate suspended from the positive pole serves a double purpose ; it not only closes the current, but it keeps the solution in a state of concentration, for the acid liberated at the positive pole dissolves the copper, and reproduces a quantity of sulphate of copper equal to that decomposed by the current.

764. **Electrogilding.**—The old method of gilding was by means of mercury. It was effected by an amalgam of gold and mercury, which was applied on the metal to be gilt. The objects thus covered were heated in a furnace, the mercury volatilised, and the gold remained in a very thin layer on the objects. The same process was used for silvering ; but they were expensive and unhealthy methods, and have now been entirely replaced by electrogilding and electrosilvering. Electrogilding only differs from the process described in the previous paragraph in that the layer is thinner and adheres more firmly. Brugnatelli, a pupil of Volta, appears to have been the first, in 1803, to observe that a body could be gilded by means of the battery and an alkaline solution of gold ; but M. de la Rive was the first who really used the battery in gilding. The methods both of gilding and silvering owe their present high state of perfection principally to the improvements of Elkington, Ruolz, and other physicists.

The pieces to be gilt have to undergo three processes before gilding.

The first consists in heating them so as to remove the fatty matter which has adhered to them in previous processes.

As the objects to be gilt are usually of copper, and their surface during the operation of heating becomes covered with a layer of suboxide or of protoxide of copper, this is removed by the second operation. For this purpose the objects, while still hot, are immersed in very dilute nitric acid, where they remain until the oxide is removed. They are then rubbed with a hard brush, washed in distilled water, and dried in gently heated sawdust.

To remove all spots they must undergo the third process, which consists in rapidly immersing them in ordinary nitric acid, and then in a mixture of nitric acid, bay salt, and soot.

When thus prepared the objects are attached to the negative pole of a battery, consisting of three or four Bunsen's or Daniell's elements. They are then immersed in a bath of gold, as previously described. They remain in the bath for a time which depends on the thickness of the desired deposit. There is great difference in the composition of the baths. That most in use consists of 1 grain of chloride of gold, 10 grains of cyanide of potassium, dissolved in 200 grains of water. In order to keep the bath in a state of concentration, a piece of gold is suspended from the positive electrode, which dissolves in proportion as the gold dissolved in the bath is deposited on the objects attached to the negative pole.

The method which has just been described can not only be used for gilding copper, but also for silver, bronze, brass, German silver, etc. But other metals, such as iron, steel, zinc, tin, and lead, are very difficult to gild well. To obtain a good coating they must first be covered with a layer of copper by means of the battery and a bath of sulphate of copper; the copper with which they are coated is then gilded, as in the previous case.

765. **Electrosilvering.**—What has been said about gilding applies exactly to the process of electrosilvering. The difference is in the composition of the bath, which consists of two parts of cyanide of silver, and two parts of cyanide of potassium dissolved in 250 parts of water. To the positive electrode is suspended a plate of silver, which prevents the bath from becoming poorer: the pieces to be silvered, which must be well cleaned, are attached to the negative pole.

CHAPTER IV.

ELECTRODYNAMICS. ATTRACTION AND REPULSION OF CURRENTS BY CURRENTS.

766. **Electrodynamics.**—Under *electrodynamics* is understood the laws of electricity in a state of motion, or the action of electric currents upon each other and upon magnets, while *electrostatics* deals with the laws of electricity in a state of rest.

The action of one electrical current upon another was first investigated by Ampère, shortly after the discovery of Oersted's celebrated fundamental experiment (739). All the phenomena, even the most complicated, follow from two simple laws, just as the theorems of geometry from the axioms. These laws are—

I. *Two currents which are parallel, and in the same direction, attract one another.*

II. *Two currents parallel, but in contrary directions, repel one another.*

In order to demonstrate these laws, the circuit which the current traverses must consist of two parts, one fixed and the other moveable. This is effected by the following apparatus (fig. 612), which is a modified and improved form of one originally devised by Ampère.

It consists of two brass columns, A and D, between which is a smaller one. The column D is provided with a multiplier of 20 turns, MN (fig. 612), which greatly increases the sensitiveness of the instrument. This can be adjusted at any height and in any position by means of an universal screw clamp (see figs. 614–616).

The small column is hollow, and in its interior glides a brass tube terminating in a mercury cup *c*, which can be raised or lowered. On the column A is another mercury cup represented in section at fig. 613 in its natural size. In the bottom is a capillary aperture through which passes the point of a sewing needle fixed to a small copper ball. This point ex-

tends as far as the mercury, and turns freely in the hole. The moveable part of the circuit consists of a copper wire proceeding from the small

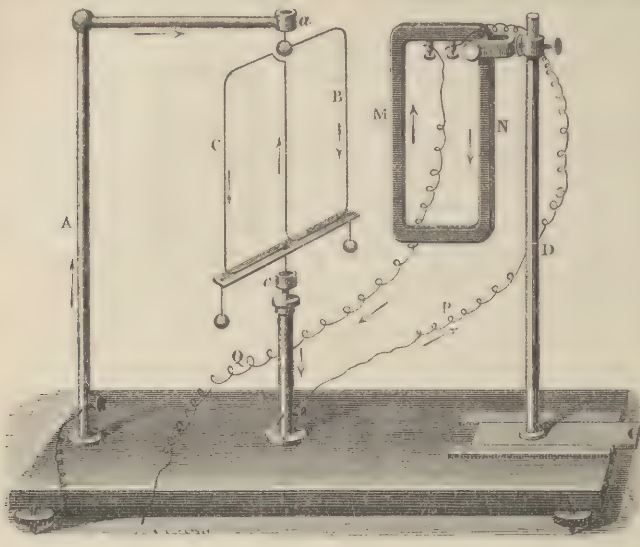


Fig. 612.

bullet, and turning in the direction of the arrows from the cup *a* to the cup *c*. The two lower branches are fixed to a thin strip of wood, and the whole system is balanced by two copper balls suspended to the ends.

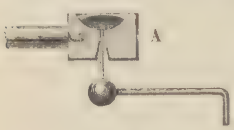


Fig. 613.

The details being known, the current of a Bunsen's battery of 4 or 5 cells ascending by the column A (fig. 612) to the cup *a*, traverses the circuit BC, reaches the cup *c*, descends the central column, and thence passes by a wire P to the multiplier MN, from whence it returns to the battery by the wire Q. Now if before the current passes, the moveable circuit has been arranged in the plane of the multiplier, the sides B and M opposite each other, when the current passes the side B is repelled, which demonstrates the second law; for in the branches B and M the currents, as indicated by the arrows, are proceeding in opposite directions.

To demonstrate the first law the experiment is arranged as in figure 614, that is, the multiplier is reversed; the current is then in the same direction both in the multiplier and in the moveable part; and when the latter is removed out of the plane of the multiplier, so long as the current passes it tends to return to it, proving that there is attraction between the two parts.

767. **Laws of angular currents.**—I. *Two rectilinear currents, the directions of which form an angle with each other, attract one another when both approach or recede from the apex of the angle.*

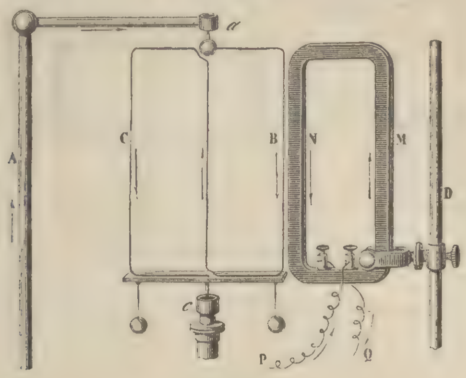


Fig. 614.

II. *They repel one another if one approaches and the other recedes from the apex of the angle.*

These two laws may be demonstrated by means of the apparatus above described, replacing the moveable circuit by the circuit BC (fig. 615). If

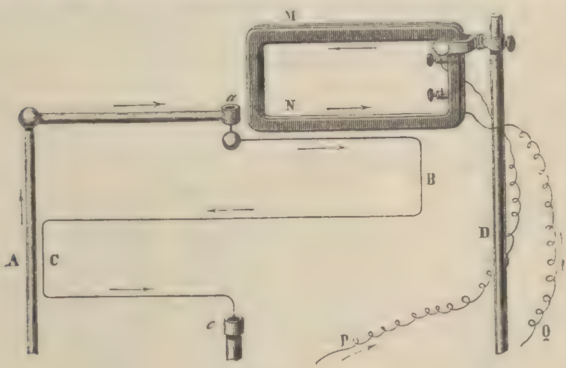


Fig. 615.

then, the multiplier is placed horizontally, so that its current is in the same direction as in the moveable current, if the latter is removed and the current passes so that the direction is the same as in the moveable part, on removing the latter it quickly approaches the multiplier, which verifies the first law.

To prove the second law the multiplier is turned so that the currents are in opposite directions, and then repulsion ensues (fig. 616).

In a rectilinear current each element of the current repels the succeeding one, and is itself repelled.

This is an important consequence of Ampère's law, and may be experi-

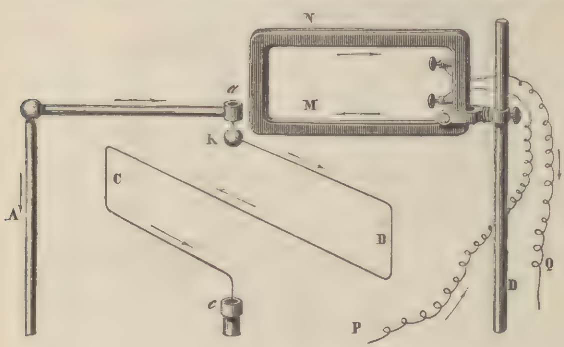


Fig. 616.

mentally demonstrated by the following arrangement, which was devised by Faraday. A U-shaped piece of copper wire, whose ends dip in two separate deep mercury cups, is suspended from one end of a delicate balance and suitably equipoised. When the mercury cups are connected with the two poles of a battery the wire rises very appreciably, and sinks again to its original position when the current ceases to pass. The current passes into the mercury and into the wire; but from the construction of the apparatus the former is fixed, while the latter is moveable, and is accordingly repelled.

768. **Laws of sinuous currents.**—*The action of a sinuous current is*

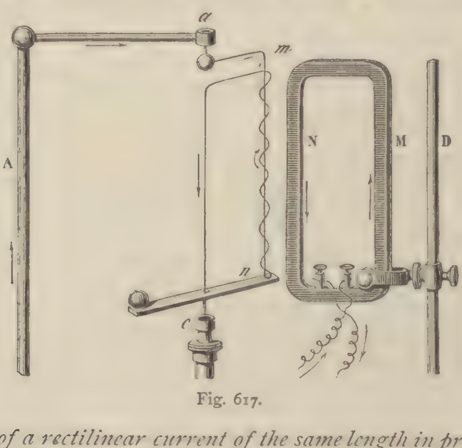


Fig. 617.

equal to that of a rectilinear current of the same length in projection. This principle is demonstrated by arranging the multiplier vertically and placing

near it a moveable circuit of insulated wire half sinuous and half rectilinear (fig. 617). It will be seen that there is neither attraction nor repulsion, showing that the action of the sinuous portion *mn* is equalled by that of the rectilinear portion *no*.

An application of this principle will presently be met with in the apparatus called *solenoids*, which are formed of the combination of a sinuous with a rectilinear current.

DIRECTION OF CURRENTS BY CURRENTS.

769. **Action of an infinite current on a current perpendicular to its direction.**—From the action exerted between two angular currents (767) the action of a fixed and infinite rectilinear current, PQ (fig. 618), on a moveable current KH, perpendicular to its direction, can be determined. Let OK be the perpendicular common to KH and PQ, which is null if the two lines PQ and KH meet. The current PQ flowing from Q to P in the direction of the arrows, let us first consider the case in which the current KH approaches the current QP. From the first law of angular currents (767) the portion QO of the current PQ attracts the current KH because they both flow towards the summit of the angle formed by their directions. The portion PO, on the contrary, will repel the current KH, for here the

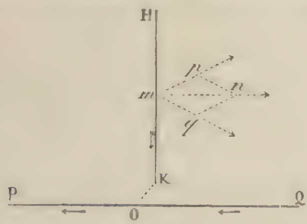


Fig. 618.

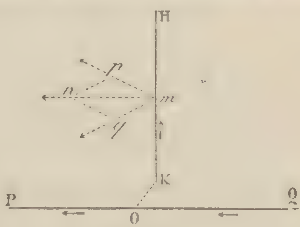


Fig. 619.

two currents are in opposite directions at the summit of the angle. If then *mq* and *mp* stand for the two forces, one attractive and the other repulsive, which act on the current KH, and which are necessarily of the same intensity, since they are symmetrically arranged in reference to the two sides of the point O, these two forces may be resolved into a single force, *mn*, which tends to move the current KH parallel to the current QP, but in a contrary direction.

On considering the case in which the current KH moves away from PQ (fig. 618) it will be readily seen from similar considerations that it moves parallel to this current, but in the same direction.

Hence follows this general principle. *A finite moveable current which approaches a fixed infinite current is acted on so as to move in a direction parallel and opposite to that of the fixed current; if the moveable current tends from the fixed current, it is acted on so as to move parallel to the current and in the same direction.*

It follows from this, that if a vertical current is moveable about an

axis, XY, parallel to its direction (figs. 620 and 621), any horizontal current, PQ, will have the effect of turning the moveable current about

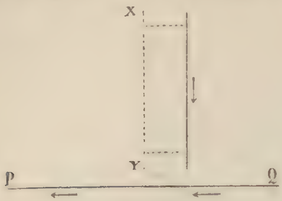


Fig. 620.

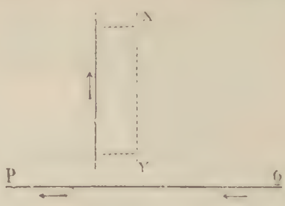


Fig. 621.

its axis, *until the plane of the axis and of the current have become parallel* to PQ ; the vertical current stopping, in reference to its axis, *on the side from which the current* PQ *comes* (fig. 620), *or on the side towards which it is directed* (fig. 621), *according as the vertical current descends or ascends*, that is, according as it approaches or moves from the horizontal axis.

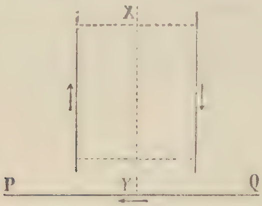


Fig. 622.

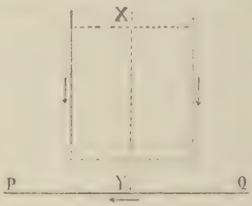


Fig. 623.

It also follows from this principle that a system of two vertical currents rotating about a vertical axis (figs. 622 and 623) is directed by a horizontal current PQ in a plane parallel to this current, when one of the vertical currents is ascending and the other descending (fig. 622), but that if they are both ascending or both descending (fig. 623) they are not directed.

770. **Action of an infinite rectilinear current on a rectangular or circular current.**—It is easy to see that a horizontal infinite current exercises the same directive action on a rectangular current moveable about a vertical axis (fig. 624), as what has been above stated. For, from the direction of the currents indicated by the arrows, the part QY acts by attraction not only on the horizontal portion YD (*law of angular currents*), but also on the vertical portion AD (*law of perpendicular currents*). The same action evidently takes place between the part PY and the parts CY and BC. Hence, *the fixed current* PQ *tends to direct the moveable rectangular current* ABCD *into a position parallel to* PQ, *and such that in the wires* CD *and* PQ *the direction of the two currents is the same.*

This principle is readily demonstrated by placing the circuit ABCD on the apparatus with two supports (fig. 631), so that at first it makes an angle

with the plane of the supports, On passing below the circuit, a somewhat powerful current in the same plane as the supports, the moveable part

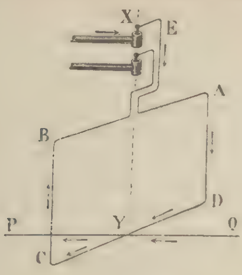


Fig. 624.

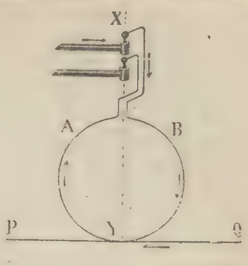


Fig. 625.

passes into that plane. It is best to use the circuit in fig. 631, which is astatic, while that of fig. 624 is not.

What has been said about the rectangular current in fig. 624 applies also to the circular current of fig. 625, and is demonstrated by the same experiments.

ROTATION OF CURRENTS BY CURRENTS.

771. **Rotation of a finite horizontal current by an infinite horizontal rectilinear current.**—The attractions and repulsions which rectangular currents exert on one another may readily be transformed into a continuous circular motion. Let OA (fig. 626) be a current moveable about the point O in a horizontal plane, and let PQ be a fixed infinite current also horizontal. As these two currents flow in the direction of the arrows, it follows that in the position OA, the moveable current is attracted by the current PQ, for they are in the same direction. Having reached the position OA′ the moveable current is attracted by the part NQ of the fixed current, and repelled by the part PN. Similarly in the position OA′ it is attracted by MQ and repelled by PM, and so on; from which follows a continuous rotatory motion in the direction AA′A″A‴. If the moveable current, instead of being directed from O towards A, were directed from

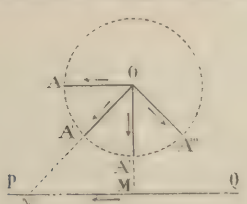


Fig. 626.

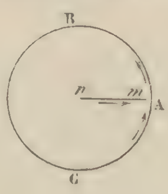


Fig. 627.

A towards O, it is easy to see that the rotation would take place in the contrary direction. Hence, by the action of a fixed infinite current, PQ,

the moveable current OA tends to a continuous motion *in a direction opposite that of the fixed current.*

If, both currents being horizontal, the fixed current were circular instead of being rectilinear, it is easily seen that its effect would still be to produce a continuous circular motion. For, let ABC (fig. 627) be a fixed circular current, and *mn* a rectilinear current moveable about the axis, *n*, both currents being horizontal. These currents, flowing in the direction of the arrows, would attract one another in the angle *n*AC, for they both flow towards the summit (767). In the angle *n*AB, on the contrary, they repel one another, for one goes towards the summit and the other moves from it. Both effects coincide in moving the wire *mn* in the same direction ACB.

772. **Rotation of a vertical current by a horizontal circular current.** —A horizontal circular current, acting on a rectilinear vertical current, also imparts to it a continuous rotatory motion. In order to show this, the apparatus represented in fig. 628 is used.

It consists of a brass vessel, round which are rolled several coils of insulated copper wire, through which a current passes. In the centre of the vessel is a brass support, *a*, terminated by a small cup containing mercury. In this dips a pivot supporting a copper wire, *bb*, bent at its extremities in two vertical branches, which are soldered to a very light copper ring immersed in acidulated water contained in the vessel. The current of a battery entering through the wire *m*, reaches the wire A, and having made several circuits, terminates at B, which is connected by a wire underneath with the lower part of the column *a*. Ascending in this column, it passes by the wires *bb* into the copper ring, into the acidulated

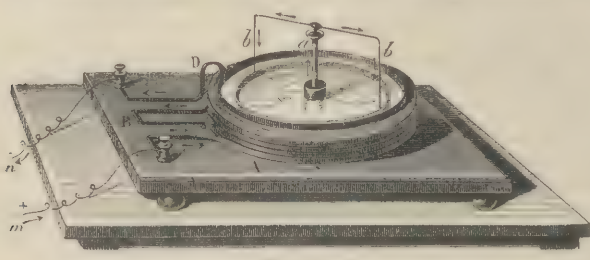


Fig. 628.

water, and into the sides of the vessel, whence it returns to the battery by the strip D. The current being thus closed, the circuit *bb* and the ring tend to turn in a direction contrary to that of the fixed current, a motion due to the action of the circular current on the current in the vertical branches *bb*; for, as follows from the two laws of angular currents, the branch *b* on the right is attracted by the portion A of the fixed current, and the branch *b* on the left is attracted in the contrary direction by the opposite part, and these two motions coincide to give the ring a continuous rotatory motion in the same direction. The action of the circular current on the horizontal part of the circuit *bb* would manifestly tend to

turn it in the same direction; but from its distance it may evidently be neglected.

773. **Rotation of magnets by currents.**—Faraday has proved that currents impart the same rotatory motions to magnets which they do to currents. This may be shown by means of the apparatus represented in fig. 629. It consists of a large glass vessel, almost filled with mercury. In the centre of this is immersed a magnet about 8 inches in length, which projects a little above the surface of the mercury; it is loaded at its lower end with a platinum cylinder, represented at *ab* on the right of the apparatus. At the top of the magnet is a small copper cup containing mercury; the current passes into this cup by the rod C. As soon as the current ascending in the column A passes into the magnet, thence into the mercury, and emerges by the column D, the magnet begins to rotate round its own axis with a velocity depending on its magnetic power, and on the intensity of the current.

This rotatory motion is readily intelligible on Ampère's theory of magnetism, which will be subsequently explained (784), according to which,

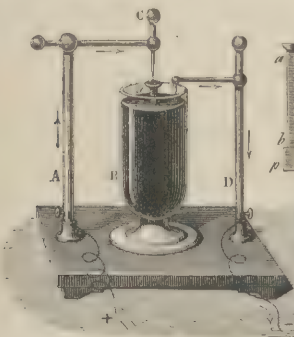


Fig. 629.

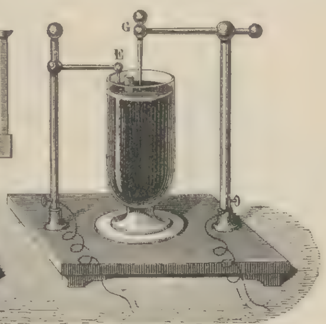


Fig. 630.

magnets are traversed on their surface by an infinity of circular currents in the same direction, in planes perpendicular to the axis of the magnet. At the moment at which the current passes from the magnet into the mercury, it is divided on the surface of the mercury into an infinity of rectilinear currents proceeding from the axis of the magnet to the circumference of the glass. Now each of these currents acts on the currents of the magnet in the same manner as, in fig. 626, the rectilinear current *mn* acts upon the circular current CAB; that is to say, that the circle CAB representing one of the currents of the magnet, there is attraction in the angle *n*AC, and repulsion in the angle *n*AB, and consequently rotation of the magnet round its axis. The action of the current merely affects the upper part of the magnet, and if the north pole is uppermost, as in the figure, the rotation is from west to east. If the north pole is below, or the direction of the current be altered, the rotation of the magnet is in the opposite direction.

Instead of making the magnet rotate on its axis, it may be caused to rotate round a line parallel to its axis by arranging the experiment as shown in fig. 630.

ACTION OF THE EARTH AND OF MAGNETS ON CURRENTS.

774. **Directive action of magnets on currents.**—Not only do currents act upon magnets, but magnets also act upon currents. In Oersted's fundamental experiment (fig. 591), the magnet being moveable while the current is fixed, the former is directed and sets at right angles with the current. If, on the contrary, the magnet is fixed and the current moveable, the latter is directed and sets across the direction of the magnet. This may be illustrated by the apparatus represented in fig. 631. This is the original form of Ampère's stand and is frequently used in experimental demonstration. It needs no explanation. The circuit which the current traverses is moveable, and below its lower branch a powerful bar magnet is placed; the circuit immediately begins to turn, and stops after some oscillations in a plane perpendicular to the axis of the magnet.

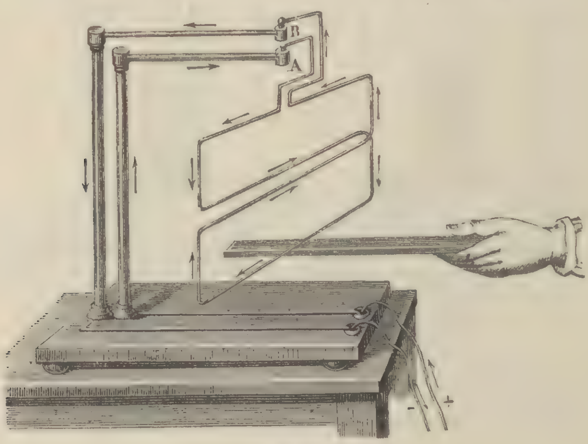


Fig. 631.

For demonstrating the action of magnets upon currents, and indeed for establishing the fundamental laws of electrodynamics, a small apparatus, known as De la Rive's *floating battery* is well adapted. It consists of a small Daniell's element, contained in a glass tube attached to a cork, so that it can float freely on water. The plates are connected with minute mercury cups on the cork float; and with these can be connected either circular or rectangular wires, coils, or solenoids; and they are then traversed by a current, and can be subjected to the action either of magnets or of currents.

775. **Rotation of currents by magnets.**—Not merely can currents be

directed by magnets, but they may also be made to rotate, as is seen from the following experiment, devised by Faraday, fig. 632. On a base with levelling screws, and resting on an ivory support, is a copper rod BD. It is surmounted in part of its length by a magnetised bundle AB, and at the top is a mercury cup. A copper circuit EF, balanced on a steel point, rests in the cup, and the other ends of the circuit, which terminate in steel points, dip in an annular reservoir full of mercury.

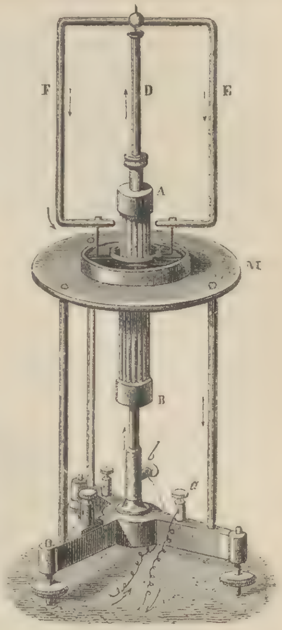


Fig. 632.

The apparatus being thus arranged, the current from 4 or 5 Bunsen's elements enters at the binding screw *b*; it thence ascends in the rod D, redescends by the two branches, reaches the mercury by the steel points, whence it passes by the framework, which is of copper, to the battery by the binding screw *a*. If now the magnetised bundle be raised, the circuit EF rotates either in one direction or the other according to the pole by which it is influenced. This rotation is due to currents assumed to circulate round magnets, currents which act on the vertical branches, EF, in the same way as the circular current on the arm in fig. 628.

In this experiment the magnetised bundle may be replaced by a solenoid (779) or by an electromagnet, in which case the two binding screws in the base of the apparatus on the left give entrance to the current which is to traverse the solenoid or electromagnet.

776. **Directive action of the earth on vertical currents.**—The earth, which exercises a directive action on magnets (629), acts also upon currents, giving them, in some cases, a fixed direction, in others a continuous rotatory motion, according as their currents are arranged in a vertical or horizontal direction.

The first of these two actions may be thus enunciated: *Every vertical current moveable about an axis parallel to itself, places itself under the directive action of the earth in a plane through this axis perpendicular to the magnetic meridian, and stops, after some oscillations, on the east of its axis of rotation when it is descending, and on the west when it is ascending.*

This may be demonstrated by means of the apparatus represented in fig. 634, which consists of two brass vessels of somewhat different diameters. The larger, *a*, about 13 inches in diameter, has an aperture in the centre, through which passes a brass support, *b*, insulated from the vessel *a*, but communicating with the vessel K. This column terminates in a small cup, in which a light wooden rod rests on a pivot. At one end of this rod

a fine wire is coiled, each end of which dips in acidulated water, with which the two vessels are respectively filled.

The current arriving by the wire *m* passes to a strip of copper, which is connected underneath the base of the apparatus with the bottom of the column *b*. Ascending in this column the current reaches the vessel K, and the acidulated water which it contains; it ascends from thence in the wire *c*, redescends by the wire *e*, and traversing the acidulated water, it reaches the sides of the vessel *a*, and so back to the battery through the wire *n*.

The current being thus closed, the wire *e* moves round the column *b* and stops to the east of it, when it descends, as is the case in the figure;

Fig. 633.

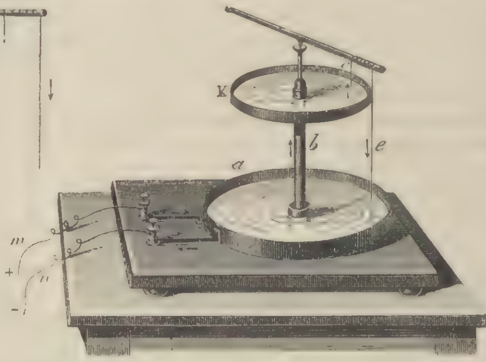


Fig. 634.

but if it ascends, which is effected by transmitting the current by the wire *n*, the wire *e* stops to the west of the column *b*, in a position directly opposite to that which it assumes when it is descending.

If the rod with a single wire, in fig. 634, be replaced by one with two wires, as in fig. 635, the rod will not move, for as each wire tends to place itself on the east of the column, *b*, two equal and contrary effects are produced, which counterbalance one another.

777. **Action of the earth on horizontal currents moveable about a vertical axis.**—The action of the earth on horizontal currents is not directive, but *gives them a continuous rotatory motion from the east to the west when the horizontal current moves away from the axis of rotation, and from the west to the east when it is directed towards this axis.*

This may be illustrated by means of the apparatus represented in fig. 635, which only differs from that of fig. 634 in having but one vessel. The current ascending by the column *a*, traverses the two wires *cc*, and descends by the wires *bb*, from which it regains the pile, the circuit *bccb* then begins a continuous rotation, either from the east to the west, or from the west to the east, according as in the wires *cc* the current goes from the centre, as is the case in the figure; or according as it goes towards it, which is the case when the current enters by the wire *m* instead of by *n*. But we have

seen (776) that the action of the earth on the vertical wires *bb* is destroyed; hence the rotation is that produced by the action on the horizontal

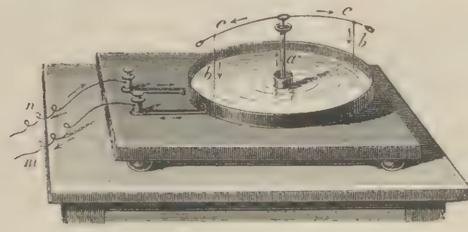


Fig. 635.

branches *cc*. This rotatory action of the terrestrial current on horizontal currents is a consequence of the rotation of a finite horizontal by an infinite horizontal current (771).

778. **Directive action of the earth on closed currents moveable about a vertical axis.**—If the current on which the earth acts is closed, whether it be rectangular or circular, the result is not a continuous rotation, but a directive action, as in the case of vertical currents (775), in virtue of which *the current places itself in a plane perpendicular to the magnetic meridian, so that, for an observer looking at the north, it is descending on the east of its axis of rotation, and ascending on the west.*

This property which can be shown by means of the apparatus represented in fig. 636, is a consequence of what has been said about horizontal and vertical currents. For in the closed circuit, BDA, the current in the upper and lower parts tends to turn in opposite directions, from the law of horizontal currents (748); and hence is in equilibrium, while in the lateral parts the current on the one side tends towards the east, and on the other side to the west, from the law of vertical currents.

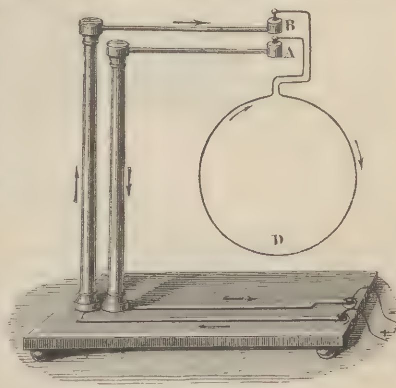


Fig. 636.

From the directive action of the earth on currents, it is necessary, in most experiments, to obviate this action. This is effected by arranging the moveable circuit symmetrically about its axis of rotation, so that the directive action of the earth tends to turn them in opposite directions, and hence destroys them. This condition is fulfilled in the circuits represented in figs. 615 and 616. Hence these currents are called *astatic currents.*

SOLENOIDS.

779. **Structure of a solenoid.**—A solenoid is a system of equal and parallel circular currents formed of the same piece of covered copper wire, and coiled in the form of a helix or spiral, as represented in fig. 636. A solenoid, however, is only complete when part of the wire BC passes in the direction of the axis in the interior of the helix. With this arrangement,

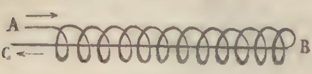


Fig. 637.

when the circuit is traversed by a current, it follows from what has been said about sinuous currents (768) that the action of a solenoid in a longitudinal direction AB is counterbalanced by that of the rectilinear current BC. This action is accordingly null in the direction of the length, and the *action of a solenoid in a direction perpendicular to its axis is exactly equal to that of a series of equal parallel currents.*

780. **Action of currents on solenoids.**—What has been said of the action of fixed rectilinear currents on finite, rectangular, or circular currents (770), applies evidently to each of the circuits of a solenoid, and

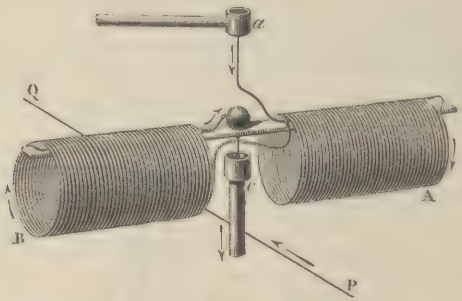


Fig. 638.

hence a rectilinear current must tend to direct these circuits parallel to itself. To demonstrate this fact experimentally, a solenoid is constructed as shown in fig. 638, so that it can be suspended by two pivots in the cups *a* and *c* of the apparatus represented fig. 612. The solenoid is then moveable about a vertical axis, and if beneath it a rectilinear current be passed which at the same time traverses the wires of the solenoid, the latter is seen to turn and set at right angles to the lower current, that is, in such a position that its circuits are parallel to the fixed current; and further, in the lower part of each of the circuits the current is in the same direction as in the rectilinear wire.

If, instead of passing a rectilinear current below the solenoid, it is passed vertically on the side, an attraction or repulsion will take place,

according, as in the vertical wire, and in the nearest part of the solenoid, the two currents are in the same or in a contrary direction.

781. **Directive action of the earth on solenoids.**—If a solenoid be suspended in the two cups (fig. 612), not in the direction of the magnetic meridian, and a current be passed through the solenoid, the latter will begin to move, and will finally set in such a position that its axis is in the direction of the magnetic meridian. If the solenoid be removed it will, after a few oscillations, return, so that its axis is in the magnetic meridian. Further, it will be found that in the lower half of the coils of which the solenoid consists, the direction of the current is from east to west ; in other words, the current is *descending* on that side of the coil turned towards the east, and ascending on the west. The directive action of the earth on solenoids is accordingly a consequence of that which it exerts on circular currents. In this experiment the solenoid is directed like a magnetic needle, and the *north pole*, as in magnets, is that end which points towards the north, and the *south pole* that which points towards the south. This experiment may be well made by means of a solenoid fitted on a De la Rive's floating battery.

782. **Mutual actions of magnets and solenoids.**—Exactly the same phenomena of attraction and repulsion exist between solenoids and magnets as between magnets. For if to a moveable solenoid traversed by a current, one of the poles of a magnet be presented, attraction or repulsion will take place, according as the poles of the magnet and of the solenoid are of contrary or of the same name. The same phenomenon takes place when a solenoid traversed by a current and held in the hand is presented to a moveable magnetic needle. Hence the law of attractions and repulsions applies exactly to the case of the mutual action of solenoids and of magnets.

783. **Mutual actions of solenoids.**—When two solenoids traversed by a powerful current are allowed to act on each other, one of them being

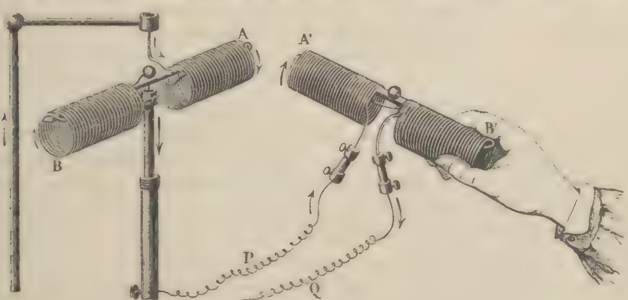


Fig. 639.

held in the hand, and the other being moveable about a vertical axis, as shown in figure 639, attraction and repulsion will take place just as in the case of two magnets. These phenomena are readily explained by refer-

ence to what has been said about the mutual action of the currents, bearing in mind the direction of the currents in the extremities presented to each other

784. **Ampère's theory of magnetism.**—Ampère has propounded a most ingenious theory, based on the analogy which exists between solenoids and magnets, by which all magnetic phenomena may be referred to electrodynamical principles.

Instead of attributing magnetic phenomena to the existence of two fluids, Ampère assumes that each individual molecule of a magnetic substance is traversed by a closed electric current. It is further assumed that these molecular currents are free to move about their centres of gravity. The coercive force, however, which is little or nothing in soft iron, but considerable in steel, opposes this motion, and tends to keep them in any position in which they happen to be. When the magnetic substance is not magnetised, these molecular currents, under the influence of their mutual attractions, occupy such positions that their total action on any external substance is null. Magnetisation consists in giving to these molecular currents a parallel direction, and the stronger the magnetising force the more perfect the parallelism. The *limit of magnetisation* is attained when the currents are completely parallel.

The resultant of the actions of all the molecular currents is equivalent to that of a single current which traverses the outside of a magnet. For by inspection of fig. 640, in which the molecular currents are represented by a series of small internal circles in the two ends of a cylindrical bar, it will be seen that the adjacent parts of the currents oppose one another, and cannot exercise any external electrodynamic action. This is not the case with the surface: there the molecular currents at *ab* are not neutralised by other currents, and as the points *abc* are infinitely near, they form a series of elements in the same direction situated in planes perpendicular to the axis of the magnet, and which constitute a true solenoid.

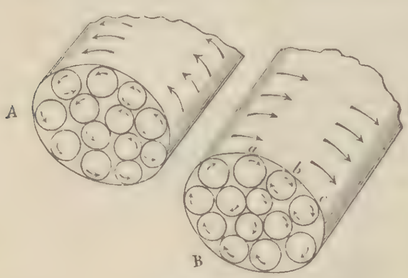


Fig. 640.

The direction of these currents in magnets can be ascertained by considering the suspended solenoid, fig. 639. If we suppose it traversed by a current, and in equilibrium in the magnetic meridian, it will set in such a position that in the lower half of each coil the current flows from *east to west*. We may then establish the following rule. *At the north pole (English) of a magnet the direction of the Ampèrian currents is opposite that of the hands of a watch, and at the south pole the direction is the same as that of the hands.*

785. **Terrestrial current.**—In order to explain on this supposition terrestrial magnetic effects, the existence of electrical currents is assumed

which continually circulate round our globe from east to west perpendicular to the magnetic meridian.

The resultant of their action is a single current traversing the magnetic equator from east to west. These currents are supposed to be thermo-electric currents due to the variations of temperature caused by the successive influence of the sun on the different parts of the globe from east to west.

These currents direct magnetic needles; for a suspended magnetic needle comes to rest when the molecular currents on its under-surface are parallel, and in the same direction as the earth currents. As the molecular currents are at right angles to the direction of its length, the needle places its greatest length at right angles to east and west, or north and south. Natural magnetisation is probably imparted in the same way to iron minerals.

CHAPTER V.

MAGNETISATION BY CURRENTS. ELECTROMAGNETS. ELECTRIC TELEGRAPHS.

786. **Magnetisation by currents.**—From the influence which currents exert upon magnets, turning the north pole to the left and the south pole to the right, it is natural to think that by acting upon magnetic substances in the natural state the currents would tend to separate the two magnetic fluids. In fact, when a wire traversed by a current is immersed in iron filings, they adhere to it in large quantities, but become detached as soon as the current ceases, while there is no action on any other non-magnetic metal.

The action of currents on magnetic substances is well seen in an experiment due to Ampère, which consists in coiling an insulated copper wire round a glass tube, in which there is an unmagnetised steel bar. If a current be passed through the wire, even for a short time, the bar becomes strongly magnetised.

If, as we have already seen, the discharge of a Leyden jar be transmitted through the wire by connecting one end with the outer coating, and the other with the inner coating, the bar is also magnetised. Hence both voltaic and frictional electricity can be used for magnetising.

Fig. 641.

If in this experiment the wire be coiled on the tube in such a manner that when it is held vertically the downward direction of the coils is from right to left on the side next the observer, this constitutes a *right-handed*

or *dextrorsal spiral* or *helix* (fig. 641), of which the ordinary screw is an example. In a *left-handed* or *sinistrorsal helix* the coiling is in the opposite direction, that is from left to right (fig. 642).

In a right-handed spiral the north pole is at the end at which the

Fig. 642.

current emerges, and the south pole at the end at which it enters ; the reverse is the case in a left-handed spiral. But whatever the direction of the coiling the polarity is easily found by the following rule : *If a person swimming in the current look at the axis of the spiral, the north pole is always on his left.* If the wire be not coiled regularly, but its direction be reversed, at each change of direction a consequent point is formed in the magnet. The simplest method of remembering the polarity produced is as follows : Whatever be the nature of the helix, either right or left handed, if the end facing the observer has the current flowing in the direction of the hands of a watch, it is a *south* pole and *vice versâ.* The same polarity is produced, whether or not an iron core be within the helix.

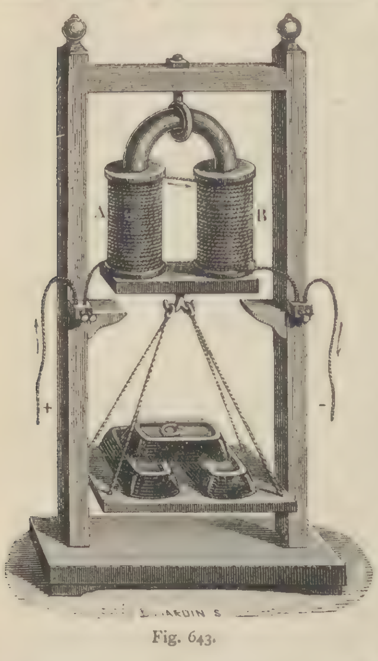


Fig. 643.

The nature of the tube on which the helix is coiled is not without influence. Wood and glass have no effect, but a thick cylinder of copper may greatly affect the action of the current unless the copper be slit longitudinally. This action will be subsequently explained. The same is the case with iron, silver, and tin.

In order, however, to magnetise a steel bar by means of electricity, it need not be placed in a tube, as shown in figs. 641 and 642. It is sufficient to coil round it a copper wire covered with silk, in order to insulate the circuits from one another. The action of the current is thus multiplied, and a feeble current is sufficient to produce a powerful charge of magnetism.

787. **Electromagnets.**—*Electromagnets* are bars of soft iron which, under the influence of a voltaic current, become magnets ; but this magnetism is only temporary, for the coercive force of perfectly soft iron is null, and the two magnetic fluids neutralise each other as soon as the

current ceases to pass through the wire. If, however, the iron is not quite pure, it retains more or less traces of magnetism. The electromagnets have the horse-shoe form, as shown in fig. 643, and a copper wire, covered with silk or cotton, is rolled several times round them on the two branches, so as to form two bobbins, A and B. In order that the two ends of the horse-shoe may be of opposite polarity, the winding on the two limbs A and B must be such that if the horse-shoe were straightened out, it would be in the same direction.

Electromagnets, instead of being made in one piece, are frequently constructed of two cylinders, firmly screwed to a stout piece of the same metal. Such are the electromagnets in Morse's telegraph (792), the electromagnetic motor (796). The helices on them must be such that the current shall flow in the same direction as the hands of a watch as seen from the south pole, and against the hands of a watch as seen from the north pole.

The results at which various experimenters have arrived as regards the force of electromagnets are often greatly divergent, which is partly due to the different senses they have attached to the notion of *electromagnetic force.* For this may mean (I.) the induction current which the development and disappearance of the magnetism of an iron core indicate in a spiral which surrounds it; this is the *excited magnetism;* or (II.) the free magnetism measured by the action on a magnetic needle, oscillating at a distance; (III.) the *attractive force*, or the force required to hold an armature at a distance from the electromagnet; (IV.) the *lifting power* measured by the force with which an armature is held in direct contact with the pole.

The most important results which have been arrived at are the following:

(i.) Using the term electromagnetic force in the first two senses it *is proportional to the intensity of the current.* This only applies when the currents are not very powerful, and to stout bars; for in each bar there is, as Muller has found, a maximum of magnetisation which cannot be exceeded.

(ii.) Taking into account the resistance, *the electromagnetic force is independent of the nature and thickness of the wire.* Thus the intensity of the current and the number of coils being the same, thick and thin wires produce the same effect.

(iii.) With the same current the *electromagnetic force is independent of the width of the coils* provided the iron projects beyond the coils, and the diameter of the coil is small compared with its length.

(iv.) The temporary magnetic moment *of an iron bar is within certain limits proportional to the number of windings.* The product of the intensity into the number of turns is usually spoken of as the *magnetising power* of the spiral. The greatest magnetising power is obtained when the resistance in the magnetising spiral is equal to the sum of the other resistances in the circuit, those of the battery included, and the length and diameter of the wire must be so arranged as to satisfy these conditions.

(v.) The magnetism in solid and in hollow cylinders of the same diameters is the same, provided in the latter case there is sufficient iron for the development of the magnetism.

(vi.) The attraction of an armature by an electromagnet is proportional to the square of the intensity of the current so long as the magnetic moment does not attain its maximum. Two unequally strong electromagnets attract each other with a force proportional to the square of the sum of both currents.

(vii.) For powerful currents the length of the branches of an electromagnet is without influence on the weight which it can support.

As regards the quality of the iron used for the electromagnet it must be pure, and be made as soft as possible by being reheated and cooled a great many times ; it is polished by means of a file so as to avoid twisting. If this is not the case the bar retains, even after the passage of the current, a quantity of magnetism which is called the *remanent magnetism.* A bundle of soft iron wires loses its magnetism more rapidly than a massive bar of the same size.

Wiedemann has proved that an analogy exists between the phenomena of magnetism and those of torsion which extends even into details. Agitations during the twisting of a wire increase the torsion, just as they increased the magnetism of a wire while under the influence of the current. The permanent torsion of iron wires is diminished by their magnetisation, as the permanent magnetism of steel bars is by their torsion ; a twisted wire loses some of its torsion by heat, as a magnet loses some of its power.

We shall presently see the numerous applications which have been made of electromagnets in electric telegraphs, in electromagnetic motors, in electric clocks, and in the study of diamagnetic phenomena.

788. **Vibratory motion and sounds produced by currents.**—When a rod of soft iron is magnetised by a strong electric current, it gives a very distinct sound, which, however, is only produced at the moment of closing or opening the current. This phenomenon, which was first observed by Page in America, and by Delezenne in France, has been particularly investigated by De la Rive, who has attributed it to a vibratory motion of the molcules of iron in consequence of a rapid succession of magnetisations and demagnetisations.

When the current is broken and closed at very short intervals, De la Rive has observed, that whatever be the shape or magnitude of the iron bars, two sounds may always be distinguished : one, which is musical, corresponds to that which the rod would give by vibrating transversely ; the other, which consists of a series of harsh sounds, corresponding to the interruptions of the current, is compared by De la Rive to the noise of rain falling on a metal roof. The most marked sound, says he, is that obtained by stretching on a sounding board pieces of soft iron wire, well annealed, from 1 to 2 mm. in diameter, and 1 to 2 yards long. These wires being placed in the axis of one or more bobbins traversed by powerful currents, send forth a number of sounds, which produce a surprising effect, and much resemble that of a number of church bells heard at a distance.

Wertheim has obtained the same sounds by passing a discontinuous current, not through the bobbins surrounding the iron wires, but through the wires themselves. The musical sound is then stronger and more sonorous in general than in the previous experiment. The hypothesis of a molecular movement in the iron wires at the moment of their magnetisation, and of their demagnetisation, is confirmed by the researches of Wertheim, who has found that their elasticity is then diminished. During magnetisation the volume of a magnet does not vary. This has been established by placing the bar to be magnetised, with its helix, in a sort of water thermometer, consisting of a flask provided with a capillary tube. On magnetising no alteration in the position of the water is observed. But the dimensions vary, the diameter is somewhat lessened, and the length increased ; according to Joule to the extent of about $\frac{1}{27000}$ if the bar is magnetised to saturation.

ELECTRIC TELEGRAPH.

789. **Electric telegraphs.**—These are apparatus by which signals can be transmitted to considerable distances by means of voltaic currents propagated in metallic wires. Towards the end of the last century, and at the beginning of the present, many philosophers proposed to correspond at a distance by means of the effects produced by electrical machines when propagated in insulated conducting wires. In 1811, Sœmmering invented a telegraph in which he used the decomposition of water for giving signals. In 1820, at a time when the electromagnet was unknown, Ampère proposed to correspond by means of magnetic needles, above which a current was sent, as many wires and needles being used as letters were required. In 1834, Gauss and Weber constructed an electromagnetic telegraph, in which a voltaic current transmitted by a wire acted on a magnetised bar ; the oscillations of which under its influence were observed by a telescope. They succeeded in thus sending signals from the Observatory to the Physical Cabinet in Göttingen, a distance of a mile and a quarter, and to them belongs the honour of having first demonstrated experimentally the possibility of electrical communication at a considerable distance. In 1837, Steinheil in Munich, and Wheatstone in London, constructed telegraphs in which several wires each acted on a single needle ; the current in the first case being produced by an electromagnetic machine, and in the second by a constant battery.

Every electric telegraph consists essentially of three parts : 1, a *circuit* consisting of a metallic connection between two places, and an *electromotor* for producing the current ; 2, a *communicator* for sending the signals from the one station ; and, 3, an *indicator* for receiving them at the other station. The manner in which these objects, more especially the last two, are effected can be greatly varied, and we shall limit ourselves to a description of the three principal methods.

The electromotor generally used in England is a modification of Wollaston's battery. It consists of a trough divided into compartments, in each of which is an amalgamated zinc plate and a copper plate ; these plates

are usually about 4½ inches in height by 3½ in breadth. The compartments are filled with sand, which is moistened with dilute sulphuric acid. This battery is inexpensive and easily worked, only requiring from time to time the addition of a little acid; but it has very low electromotive force and considerable resistance, and when it has been at work for some time, the effects of polarisation begin to be perceived. On the telegraphs of the South Eastern Railway, the platinised graphite (731) battery invented by Mr. C. V. Walker is used with success. In France, Daniell's battery is used for telegraphic purposes.

The connection between two stations is made by means of galvanised

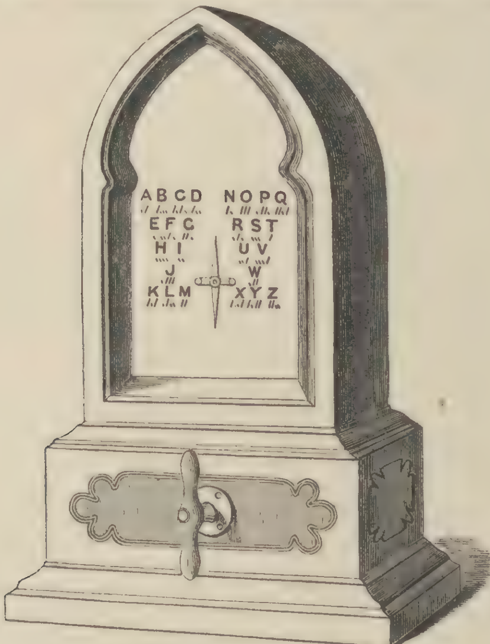


Fig. 644.

iron wire suspended by porcelain supports, which insulate and protect them against the rain, either on posts or against the sides of buildings. In towns, wires covered with gutta-percha are placed in tubes laid in the ground. Submarine cables are formed of copper wires for the sake of the greater conductivity. These wires are coated with gutta-percha, round which is a coating of tarred hemp, the whole being surrounded by an iron cable, which gives it strength to resist the tension at the moment of laying the cable, and to enable it to resist the action of submarine currents.

At the station which sends the despatch, the line is connected with the positive pole of a battery, the current passes by the line to the other station,

and if there were a second return line, it would traverse it in the opposite direction to return to the negative pole. In 1837, Steinheil made the very important discovery that the earth might be used for the return conductor, thereby saving the expense of the second line. For this purpose the end of the conductor at the one station, and the negative pole of the battery at the other, are connected with large copper plates, which are sunk to some depth in the ground. The action is then the same as if the earth acted as a return wire. The earth is, indeed, far superior to a return wire; for the added resistance of such a wire would be considerable, whereas the resistance of the earth beyond a short distance is absolutely *nil.* The earth really *dissipates* the electricity, and does not actually return the same current to the battery.

790. **Wheatstone's and Cooke's single needle telegraph.**—This consists essentially of a vertical multiplier with an astatic needle, the arrangement of which is seen in fig. 645, while fig. 644 gives a front view of the

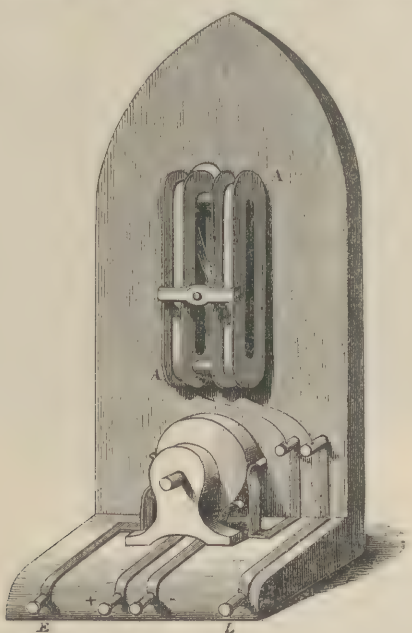


Fig. 645.

case in which the apparatus is placed. A (fig. 645) is the bobbin consisting of about 400 feet of fine copper wire, wound in a frame in two connected coils. Instead of an astatic needle, Mr. Walker has found it advantageous to use a single needle formed of several pieces of very thin steel strongly magnetised; it works within the bobbin, and a light index

joined to it by a horizontal axis indicates the motion of the needle on the dial.

The signs are made by transmitting the current in different directions through the multiplier, by which the needle is deflected either to the right or left, according to the will of the operator. The instrument by which this is effected is a *commutator* or *key*, G; its construction is shown in fig. 645, while fig. 646 shows on a large scale how two stations are connected. It consists of a cylinder of boxwood with a handle, which projects in front of the case (fig. 644). On its circumference parallel to the axis are seven brass strips (fig. 646), the spaces between which are insulated by ivory; these strips are connected at the end by metallic wires, also insulated from each other, in the following manner: *a* with *b* and *c*, *f* with *d*, and *e* with *g*. Four springs press against the cylinder; *x*

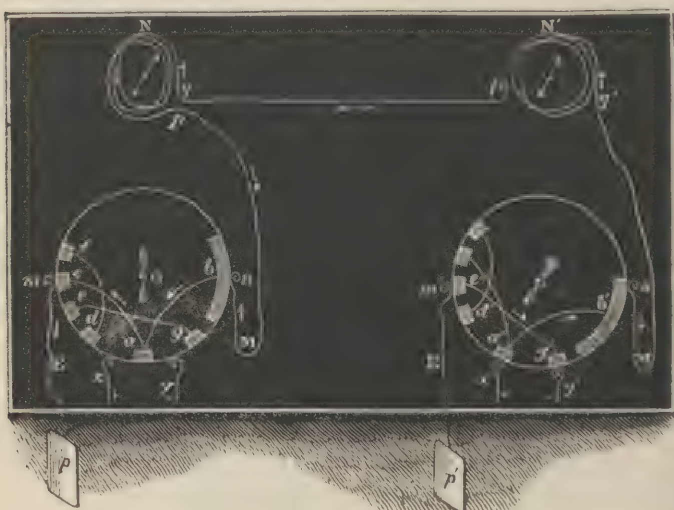


Fig. 646.

and *y* are connected with the poles of the battery, *m* with the earth plate, and *n* with one end of the multiplier, N.

When not at work the cylinder and the handle are in a vertical position, as seen on the left of the diagram. The circuit is thus *open*, for the pole springs, *x* and *y*, are not connected with the metal of the commutator. But if, as in G′, the key is turned to the right, the battery is brought into the circuit, and the current passes in the following direction + pole $x'a'b'n'M'q'$, conductor $qMnbacmEp$, earth $p'E'm'e'g'y'$ – pole. The coils N and N′ are so arranged that by the current the motion of the needle corresponds to the motion of the handle. By turning the handle to the left the current would have the following direction: + pole $x'd'f'm'E'p'$,

earth $pEmcabnMq$, conductor $q'M'n'b'a'y'$ – pole, and thus the needle would be deflected in the opposite direction.

The signs are given by differently combined deflections of the needle, as represented in the alphabet on the dial (fig. 644). ╲ denotes a deflection of the upper end of the needle to the left, and ╱ a deflection to the right; I, for instance, is indicated by two deflections to the left, and M by two to the right. Some of the marks on the alphabet are only half as long as the others; this indicates that the shortest of the connected marks must first be signalled. Thus, D is expressed by right-left-left, and C by right-left-right-left, etc.

These signs are somewhat complicated, and require great practice; usually not more than 12 to 20 words can be sent in a minute. Hence the single needle telegraph is in most cases replaced by the double needle one, which is constructed on the same principle, but there are two needles and two wires instead of one.

791. **Dial telegraphs.**—Of these many kinds exist. Figs 648 and 649 represent a lecture-model of one form, constructed by M. Froment, and which well serves to illustrate the principle. It consists of two parts: the *manipulator* for transmitting signals (fig. 648), and the *indicator* (fig. 649) for receiving them. The first apparatus is connected with a battery, Q, and the two apparatus are in communication by means of metallic wires, one of which, AOD (fig. 648), goes from the departure to the arrival station, and the other, HKLI (fig. 649), from the arrival to the departure. In practice, the latter is replaced by the earth circuit. Each apparatus is furnished with a dial with 25 of the letters of the alphabet, on which a needle moves. The needle at the departure station is moved by hand, that of the arrival by electricity.

The path of the current and its effects are as follows: From the battery it passes through a copper wire, A (fig. 648), into a brass spring N, which presses against a metal wheel, R, then by a second spring, M, into the wire, O, which joins the other station. Thence the current passes into the bobbin of an electromagnet, b, not fully shown in fig. 649, but of which fig. 647 represents a section, showing the anterior part of the apparatus. This electromagnet is fixed horizontally at one end, and at the other it attracts an armature of soft iron, a, which forms part of a bent lever, moveable about its axis, o, while a spring, r, attracts the lever in the opposite direction.

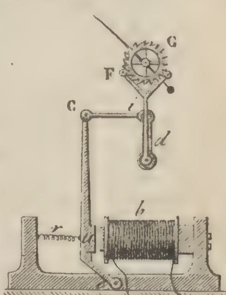


Fig. 647.

When the current passes, the electromagnet attracts the lever aC, which by a rod, i, acts on a second lever, d, fixed to a horizontal axis, itself connected with a fork F. When the current is broken the spring r draws the lever aC, and therewith all the connected pieces; a backward and forward motion is produced, which is communicated to the fork, F, which transmits it to a toothed wheel, G, on the axis of which is the needle. From the arrangement

of its teeth, the wheel G is always moved in the same direction by the fork.

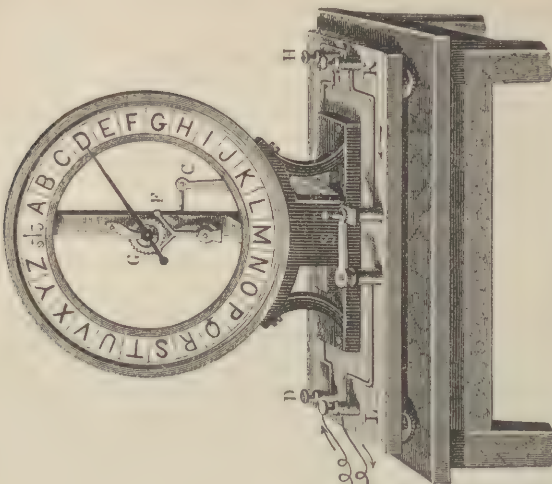


Fig. 649.

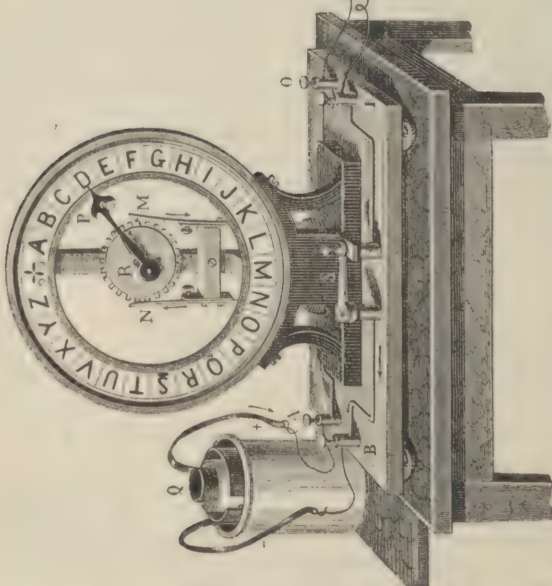


Fig. 648.

To explain the intermittent action of the magnet, we must refer to fig. 648. The toothed wheel, R, has 26 teeth, of which 25 correspond to

letters of the alphabet, and the last to the interval reserved between the letters A and Z. When holding the knob P in the hand the wheel R is turned, the end of the plate N from its curvature is always in contact with the teeth ; the plate M, on the contrary, terminates in a catch cut so that contact is alternately made and broken. Hence the connections with the battery having been made, if the needle P is advanced through four letters, for example, the current passes four times in N and M, and is four times broken. The electromagnet of the arrival station will then have attracted four times, and have ceased to do so four times. Lastly, the wheel G will have turned by four teeth, and as each tooth corresponds to a letter, the needle of the arrival station will have passed through exactly the same number of letters as that of the departure station. The piece S, represented in the two figures, is a copper plate, moveable on a hinge, which serves to interrupt or to close the current at will.

From this explanation it will be readily intelligible how communications are made between different places. Suppose, for example, that the first apparatus being at London and the second at Brighton, there being metallic connection between the two towns, it is desired to send the word *signal* to the latter town : as the needles correspond on each apparatus to the interval retained between A and Z, the person sending the despatch moves the needle P to the letter S, where it stops for a very short time ; as the needle at Brighton accurately reproduces the motion of the London needle it stops at the same letter, and the person who receives the despatch notes this letter. The one at London always continuing to turn in the same direction, stops at the letter I, the second needle immediately stops at the same letter; and continuing in the same manner with the letters G, N, A, L, all the word is soon transmitted to Brighton. The attention of the observer at the arrival station is attracted by means of an electric alarum. Each station further must be provided with the two apparatus (figs. 647 and 648), without which it would be impossible to answer.

792. **Morse's telegraph.**—The telegraphs hitherto described leave no trace of the despatches sent, and if any errors have been made in copying the signals there is no means of remedying them. These inconveniences are not met with in the case of the *writing telegraphs*, in which the signs themselves are printed on a strip of paper at the time at which they are transmitted.

Of the numerous printing and writing telegraphs which have been devised, that of Mr. Morse, first brought into use in North America, is best known. It has been almost universally adopted on the Continent. In this instrument there are three distinct parts : the *indicator*, the *communicator*, and the *relay* ; figs. 650, 651, and 652 represent these apparatus.

Indicator. We will first describe the indicator (fig. 650,) leaving out of sight for the moment the accessory pieces, G and T, placed on the right of the figure. The current which enters the indicator by the wire, C, passes into an electromagnet, E, which, when the current is closed, attracts an armature of soft iron, A, fixed at the end of a horizontal lever

moveable about an axis, x; when the current is open the lever is raised by a spring, r. By means of two screws, m and v, the amplitude of the oscillations is regulated. At the other end of the lever there is a pencil,

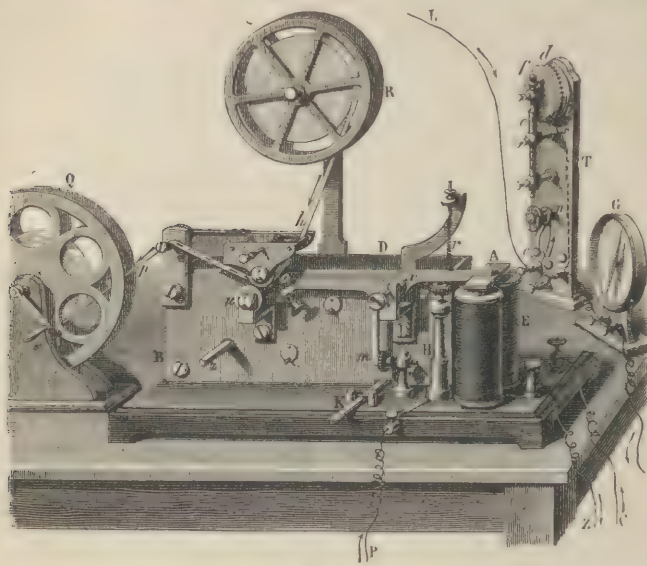


Fig. 650.

o, which writes the signals. For this purpose a long band of strong paper, *pp*, rolled round a drum, R, passes between two copper rollers with a rough surface, u, and turning in contrary directions. Drawn in the direction of the arrows, the band of paper becomes rolled on a second drum, Q, which is turned by hand. A clockwork motion placed in the box, BD, works the rollers, between which the band of paper passes.

The paper being thus set in motion, whenever the electromagnet works, the point o strikes the paper, and, without perforating it, produces an indentation, the shape of which depends on the time during which the point is in contact with the paper. If it only strikes it instantaneously, it makes a *dot* (.) or short stroke (–); but if the contact has any duration a *dash* of corresponding length is produced. Hence, by varying the length of contact of the transmitting key at one station, a combination of dots and dashes may be produced at another station, and it is only necessary to give a definite meaning to these combinations.

The same telegraphic alphabet is now universally used wherever telegraphic communication exists; and the signals for the single needle instrument (fig. 644) as well as those used for printing have been modified, so that they now correspond to each other. Thus a beat of the top of

the needle to the left / is equivalent to a dot; and a beat to the right \ to a dash. The following is the alphabet:

PRINTING.	SINGLE NEEDLE.	PRINTING.	SINGLE NEEDLE.
A - —	\/	N — -	/\
B — - - -	/\\\	O — — —	///
C — - — -	/\/\	P - — — -	\//\
D — - -	/\\	Q — — - —	//\/
E -	\	R - — -	\/\
F - - — -	\\/\	S - - -	\\\
G — — -	//\	T —	/
H - - - -	\\\\	U - - —	\\/
I - -	\\	V - - - —	\\\/
J - — — —	\///	W - — —	\//
K — - —	/\/	X — - - —	/\\/
L - — - -	\/\\	Y — - — —	/\//
M — —	//	Z — — - -	//\\

Communicator or key. This consists of a small mahogany base, which acts as support for a metallic lever *ab* (fig. 651), moveable in its middle on a horizontal axis. The extremity *a* of this lever is always pressed upwards by a spring beneath, so that it is only by pressing with the finger

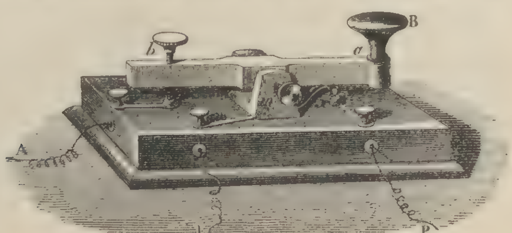


Fig. 651.

on the key B that the lever sinks and strikes the button *x*. Round the base there are three binding screws; one connected with the wire P, which comes from the positive pole of the battery; the second connected with L, the wire of the line; and the third with the wire A, which passes to the indicator, for of course two places in communication are each provided with an indicator and communicator.

These details known, there are two cases to be considered: 1. The communicator is arranged so as to receive a despatch from a distant post; the extremity *b* is then depressed, as represented in the drawing, so that the current which arrives by the wire of the line L, and ascends in the metallic piece *m*, redescends in the wire A, which leads it to the indicator of the post at which the apparatus is placed. 2. A despatch is to be transmitted; in this case the key B is pressed so that the lever comes in contact with the button *x*. The current of the local battery, which comes by the wire P, ascending then in the lever, redescends by *m* and joins the wire L, which conducts it to the post to which the despatch is addressed. According to the length of time during which B is pressed, a dot or a line is produced in the receiver to which the current proceeds.

Relay. In describing the receiver we have assumed that the current of the line coming by the wire C (fig. 650) entered directly into the electromagnet. and worked the armature A, producing a despatch; but when the current has traversed a distance of a few miles its intensity has diminished so greatly that it cannot act upon the electromagnet with sufficient force to print a despatch. Hence it is necessary to have recourse to a relay, that is, to an auxiliary electromagnet which is still traversed by the current of the line, but which serves to introduce into the communicator the current of a *local battery* of 4 or 5 elements placed at the station, and only used to print the signals transmitted by the wire.

For this purpose the current entering the relay by the binding screw, L (fig. 652) passes into an electromagnet E, whence it passes into the

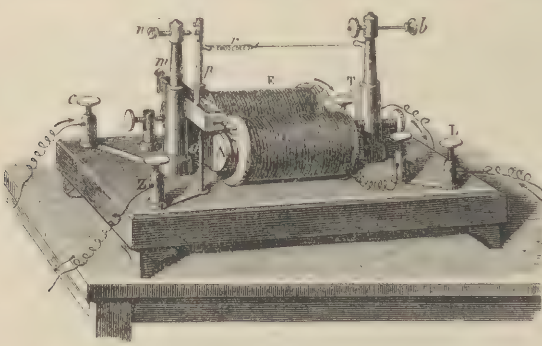


Fig. 652.

earth by the binding screw T. Now, each time that the current of the line passes into the relay, the electromagnet attracts an armature, A, fixed at the bottom of a vertical lever *p*, which oscillates about a horizontal axis.

At each oscillation the top of the lever *p* strikes against a button, *n*, and at this moment the current of the local battery which enters by the binding screw, *c*, ascends the column *m*, passes into the lever *p*, descends

by the rod *o*, which transmits it to the screw Z : thence it enters the electromagnet of the indicator, whence it emerges by the wire Z, to return to the local battery from which it started. Then when the current of the line is open, the electromagnet of the relay does not act, and the lever *p*, drawn by a spring *r*, leaves the button *n*, as shown in the drawing, and the local current no longer passes. Thus the relay transmits to the indicator exactly the same phases of passage and intermittence as those effected by the manipulator in the post which sends the despatch.

With a general battery of 25 Daniell's elements the current is strong enough at upwards of 90 miles from its starting-point to work a relay. For a longer distance a new current must be taken, as will be seen in the paragraph on the change of current (*vide infra*).

Working of the three apparatus. The three principal pieces of Morse's apparatus being thus known, the following is the actual path of the current.

The current of the line coming by the wire L (fig. 652) passes at first to the piece T intended to serve as lightning conductor, when, from the influence of atmospheric electricity in time of storm, the conducting wires become charged with so much electricity as to give dangerous sparks. This apparatus consists of two copper discs, *d* and *f*, provided with teeth on the sides opposite each other, but not touching. The disc *d* is connected with the earth by a metallic plate at the back of the stand which supports this lightning conductor, while the disc *f* is in the current. The latter coming by the line L enters the lightning conductor by the binding screw fixed at the lower part of the stand on the left ; then rises to a commutator, *n*, which conducts it to a button, *c*, whence it reaches the disc *f* by a metallic plate at the back of the stand ; in case a lightning discharge should pass along the wire, it would now act inductively on the disc *d*, and emerge by the points without danger to those about the apparatus. Moreover, from the disc *f*, the current passes into a very fine iron wire insulated on a tube *e*. As the wire is melted, when the discharge is too intense, the electricity does not pass into the apparatus, which still further removes any danger.

Lastly, the current proceeds from the foot of the support *s* to a screw on the right, which conducts it to a small galvanometer, G, serving to indicate by the deflection of the needle whether the current passes. From this galvanometer the current proceeds to a communicator (fig. 651) which it enters at L, whence it emerges at A to go to the relay (fig. 652). Entering this at L it works the electromagnet, and establishes the communication necessary for the passage of the current of the local battery, as has been said in speaking of the relay.

Change of current. To complete this description of Morse's apparatus it must be observed that in general the current which arrives at L, after having traversed 6 miles, has not sufficient force to register the despatch, nor to proceed to a new distant point. Hence, in each telegraphic station a new current must be taken, that of the *postal battery*, which consists of 20 to 30 Daniell's elements, and is not identical with the *local battery*.

This new current enters at P (fig. 650), reaches a binding screw which conducts it to the column H, and thence only proceeds further when the armature A sinks. A small contact placed under the lever touches then the button v; the current proceeds from the column H to the metallic mass BD, whence by a binding screw and a wire, not represented in the figure, it reaches lastly the wire of the line, which sends it to the following post, and so on from one post to another.

793. **Induction in telegraph cables.**—In the earliest experiments on the use of insulated subterranean wires for telegraphic communication it was found that difficulties occurred in their use which were not experienced with overland wires. This did not arise from defective insulation, for the better the insulation the greater the difficulty. It was suspected by Siemens and others that the retardation was due to statical induction taking place between the inner wire through the insulator and the external moisture; and that this was the case Faraday proved by the following experiments among others. A length of about 100 miles of gutta-percha covered copper wire was immersed in water, the ends being led into the chamber of observation. When the pole of a battery containing a large number of cells was momentarily connected with one end of the wire the other end being insulated, and a person simultaneously touched the wire and the earth contact, he obtained a violent shock.

When the wire, after being in momentary contact with the battery, was placed in connection with a galvanometer, a considerable deflection was observed; there was a feebler one 3 or 4 minutes after, and as long as 20 or 30 minutes afterwards.

When the insulated galvanometer was permanently connected with one end of the wire, and then the free end of the galvanometer wire joined to the pole of the battery, a rush of electricity through the galvanometer into the wire was perceived. This speedily diminished and the needle ultimately came to rest. When the galvanometer was detached from the battery and put to earth, the electricity flowed as rapidly out of the wire, and the needle was momentarily deflected in the opposite direction.

These phenomena are not difficult to explain. The wire with its thin insulating coating of gutta-percha becomes statically charged with electricity from the battery. The coating of gutta-percha through which the inductive action takes place is only $\frac{1}{12}$ of an inch in thickness, and the extent of the coatings is very great. The surface of the copper wire amounts to 8,300 square feet, and that of the outside coating is four times as much. The tension can only be as great as that of the battery, but from the enormous surface the quantity is very great. Thus the wires, after being detached from the battery, showed all the actions of a powerful electric battery. These effects cannot take place with wires in air, for the external coating is wanting, or at all events is so distant that induction and charge cannot occur.

Hence the difficulty in submarine telegraphy. The electricity which enters the insulating wire must first be used in charging the large Leyden jar which it constitutes, and only after this has happened can the current reach the distant end of the circuit. The current begins later at the

distant end, and ceases sooner. If the electrical currents follow too rapidly, an uninterrupted current will appear at the other end, which indicates small differences in strengh, but do not with sufficient clearness differences in duration or direction. Hence in submarine wires the signals must be slower than in air wires to obtain clear indications. By the use of alternating currents, that is, of currents which are alternately positive and negative, their disturbing influences may be materially lessened, and communication be accelerated and made more certain, but they can never be entirely obviated.

In the Atlantic Cable instruments on the principle of Thomson's reflecting galvanometer are used for the reception of signals, the motion of the spot of light to the right and left forming the basis of the alphabet.

794. **Bain's electrochemical telegraph.**—If a strip of paper be soaked in an aqueous solution of ferrocyanide of potassium and connected with the negative pole of a battery, and if the other face be touched with a steel pointer connected with the positive pole, a blue mark due to the formation of some Prussian blue will be formed about the iron, so long as the current passes. The first telegraph based on this principle was invented by Mr. Bain. The alphabet is the same as Morse's, but the despatch is first composed at the departure station on a long strip of ordinary paper. It is perforated successively by small round and elongated holes, which correspond respectively to the dots and marks. This strip of paper is interposed between a small metal wheel and a metal spring, both forming part of the circuit. The wheel in turning carries with it the paper strip, all parts of which pass successively between the wheel and the plate. If the strip were not perforated it would, not being a conductor, constantly offer a resistance to the passage of the current ; but, in consequence of the holes, every time one of them passes there is contact between the wheel and the plate. Thus the current works the relay of the post to which it is sent, and traces in blue, on a paper disc, impregnated with ferrocyanide, the same series of points and marks as those on the perforated paper.

795. **Electrical clocks.**—Electrical clocks are clockwork machines, in which an electromagnet, by means of an electric current regularly interrupted, is both the motor and the regulator. Fig. 653 represents the face of such a clock, and fig. 654 the mechanism, which works the needles.

An electromagnet, B, attracts an armature of soft iron, P, moveable on a pivot, *a*. The armature P transmits its oscillating motion to a lever, *s*, which, by means of a ratchet, *n*, turns the wheel, A. This, by the pinion, D, turns the wheel C, which by a series of wheels and pinions moves the hands. The small one marks the hours, the large one the minutes ; but as the latter does not move regularly, but by sudden starts from second to second, it follows that it may also be used to indicate the seconds.

It is obvious that the regularity of the motion of the hands depends on the regularity of the oscillations of the piece P. For this purpose, the

oscillations of the current, before passing into the electromagnet B, are regulated by a standard clock, which itself has been previously regulated

Fig. 653.

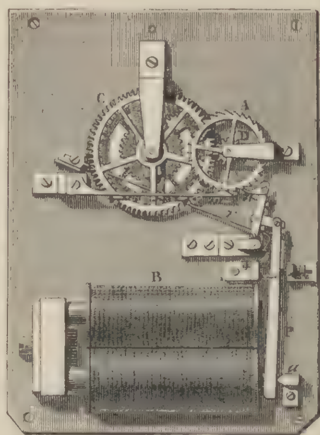


Fig. 654.

by a seconds pendulum. At each oscillation of the pendulum the current is open and closed, and thus the armature P beats seconds exactly.

To illustrate the use of these electrical clocks, suppose that on the railway from London to Birmingham each station has an electric clock, and that from the London station a conducting wire passes to all the clocks on the line as far as Birmingham. When the current passes in this wire all the clocks will simultaneously indicate the same hour, the same minute, and the same second ; for electricity travels with such enormous velocity, that it takes an inappreciable time to go from London to Birmingham.

796. **Electromagnetic machines.**—Numerous attempts have been made to apply electromagnetism as a motive force in machines. Fig. 655 represents a machine of this kind constructed by M. Froment. It consists of four powerful electromagnets ABCD fixed on an iron frame, X. Between these electromagnets is a system of two iron wheels moveable on the same horizontal axis, with eight soft iron armatures, M, on their circumference.

The current arrives at K, ascends in the wire E, and reaches a metallic arc O, which serves to pass the current successively into each electromagnet, so that the attractions exerted on the armatures M shall always be in the same direction. Now this can only be the case provided the current is broken in each electromagnet just when an armature comes in front of the axis of the bobbin. To produce this interruption the arc O has three branches, *e*, each terminating with a steel spring, to which a small sheave is attached. Two of these establish the communication

respectively with an electromagnet, and the third with two. On a central wheel, *a*, there are cogs, on which the sheaves alternately rest.

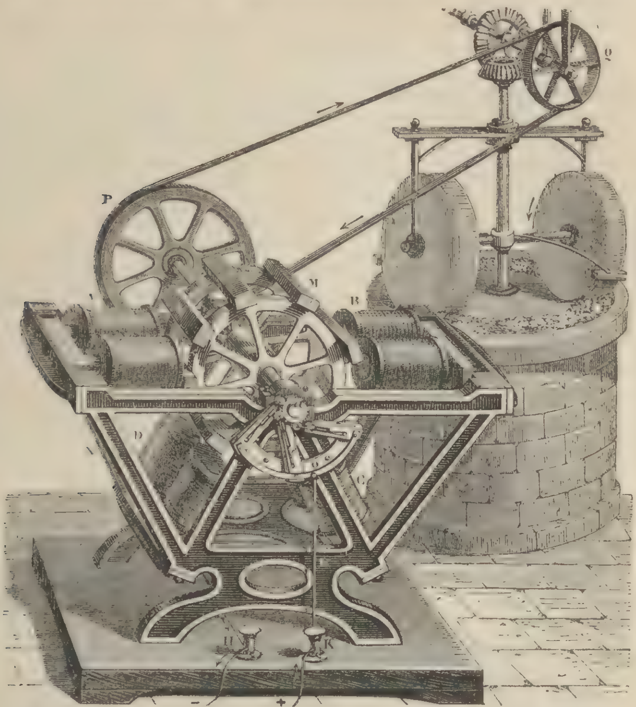


Fig. 655.

Whenever one of them rests on a cog, the current passes into the corresponding electromagnet, but ceases to pass when there is no longer contact. On emerging from the electromagnets the current passes to the negative pole of the battery by the wire H.

In this manner, the armatures M being successively attracted by the four electromagnets, the system of wheels which carries them assumes a rapid rotatory motion, which by the wheel P and an endless band is transmitted to a sheave Q, which sends it finally to any machine, a grinding mill for example.

In his workshops M. Froment has an electromotive engine of one-horse power. But as yet these machines have not been applied in manufactures, for the expense of the acids and the zinc which they use very far exceeds that of the coal in steam engines of the same force. Until some cheaper source of electricity shall have been discovered there is no expectation that they can be applied at all advantageously.

CHAPTER VI.

VOLTAIC INDUCTION.

797. **Induction by currents.**—We have already seen (670) that under the name *induction* is meant the action which electrified bodies exert at a distance on bodies in the natural state. Hitherto we have only had to deal with electrostatical induction; we shall now see that dynamical electricity produces analogous effects.

Faraday discovered this class of phenomena in 1832, and he gave the name of *currents of induction* or *induced currents* to instantaneous currents developed in metallic conductors under the influence of metallic conductors traversed by electric currents, or by the influence of powerful magnets, or even by the magnetic action of the earth; and the currents which give rise to them he has called *inducing currents.*

The inductive action of currents at the moment of opening or closing may be shown by means of a bobbin with two wires. This consists (fig. 656) of a cylinder of wood or of cardboard, on which a quantity of silk-covered No. 16 copper wire is coiled; on this is coiled a considerably

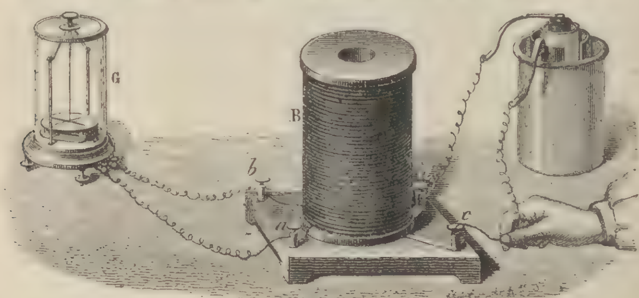


Fig. 656.

greater length of fine copper wire, about No. 35, also insulated by being covered with silk. This latter coil, which is called the *secondary coil*, is connected by its ends with two binding screws *a*, *b*, from which wires pass to a galvanometer, while the thicker wire, the *primary coil*, is connected by its extremities with two binding screws *c* and *d*. One of these *d*, being connected with one pole of a battery, when a wire from the other pole is connected with *c*, the current passes in the primary coil, and in this alone. The following phenomena are then observed:—

i. At the moment at which the thick wire is traversed by the current the galvanometer by the deflection of the needle indicates the existence in the *secondary coil* of a current *inverse* to that in the primary coil, that is, in the contrary direction; this is only instantaneous, for the needle

immediately reverts to zero, and remains so long as the inducing current passes through *cd*.

ii. At the moment at which the current is opened, that is, when the wire *cd* ceases to be traversed by a current, there is again produced in the wire *ab* an induced current instantaneous like the first, but *direct*, that is, in the same direction as the inducing current.

798. **Production of induced currents by continuous ones.**—Induced currents are also produced when a primary coil traversed by a current is approached to or removed from a secondary one: this may be shown by the following apparatus, fig. 657, in which B is a hollow coil consisting of a great length of fine wire, and A a coil consisting of a shorter and thicker wire, and of such dimensions that it can be placed in the secondary coil.

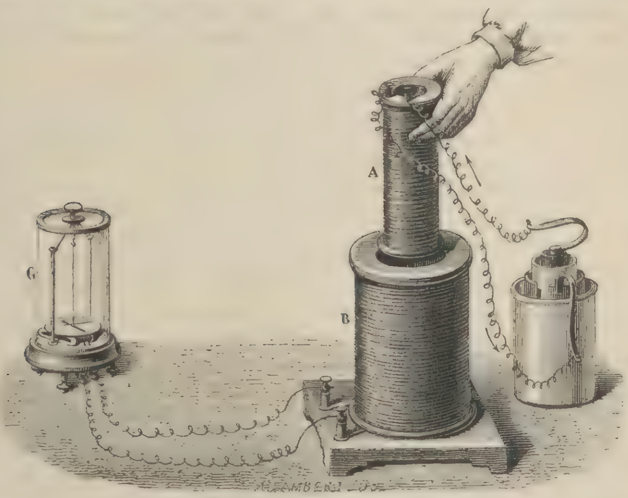


Fig. 657.

The coil A being traversed by a current, if it is suddenly placed in the coil B, a galvanometer connected with the latter indicates by the direction of its deflection the existence in it of an *inverse* current; this is only instantaneous, the needle rapidly returns to zero, and remains so long as the small bobbin is in the large one. If it is rapidly withdrawn, the galvanometer shows that the wire is traversed by a direct current. If instead of rapidly introducing or replacing the primary coil this is done slowly, the galvanometer only indicates a weak current, and which is the feebler the slower the motion.

If instead of varying the distance of the inducing current its intensity be varied, that is, either increased by bringing additional battery power into the circuit, or diminished by increasing the resistance, an induced current is produced in the secondary wire, which is inverse if the intensity of the inducing current increases and direct if it diminishes.

799. **Conditions of induction. Lenz's law.**—From the experiments which have been described in the previous paragraphs the following principles may be deduced:—

I. The distance remaining the same *a continuous and constant current does not induce any current in an adjacent conductor.*

II. *A current at the moment of being closed produces in an adjacent conductor an inverse current.*

III. *A current at the moment it ceases produces a direct current.*

IV. *A current which is removed or whose intensity diminishes, gives rise to a direct induced current.*

V. *A current which is approached, or whose intensity increases, gives rise to an inverse induced current.*

VI. On the induction produced between a close circuit and a current in activity when their relative distance varies, Lenz has based the following law, which is known as *Lenz's law:—*

If the relative position of two conductors A and B be changed, of which A is traversed by a current, a current is induced in B in such a direction, that by its electrodynamic action on the current in A, it would have imparted to the conductors a motion of the contrary kind to that by which the inducing action was produced.

Thus, for instance, in V, when a current is approached to a conductor, an inverse current is produced; but two conductors traversed by currents in opposite directions, *repel* one another according to the received law of electrodynamics. Inversely when a current is *moved away from* a conductor a current of the same direction is produced; but two currents in the same direction *attract* one another.

On bringing the inducing wire near the induced as well as in removing it away work is required; hence a quantity of heat proportional to the work consumed must result, as Edlund's investigations have shown. On the other hand, when induction results from the opening and closing of the circuit (II. and III.) no work is lost, but the inducing current loses as much heat as is produced in the induced circuit.

800. **Inductive action of the Leyden discharge.**—Figure 658 represents an apparatus devised by Matteucci, which is very well adapted for showing the development of induced currents produced either by the discharge of a Leyden jar or by the passage of a voltaic current.

It consists of two glass plates about 12 inches diameter, fixed vertically on the two supports A and B. These supports are on moveable feet, and can either be approached or removed at will. On the anterior face of the plate A are coiled about 30 yards of copper wire, C, a millimeter in diameter. The two ends of this wire pass through the plate, one in the centre, the other near the edge, terminating in two binding screws, like those represented in *m* and *n*, on the plate B. To these binding screws are attached two copper wires, *c* and *d*, through which the inducing current is passed.

On the face of the plate B, which is towards A, is enrolled a spiral of much finer copper wire than the wire C. Its extremities terminate in the binding screws *m* and *n*, on which are fixed two wires, *h* and *i*, intended

to transmit the induced current. The two wires on the plates are not only covered with silk, but each circuit is insulated from the next one by

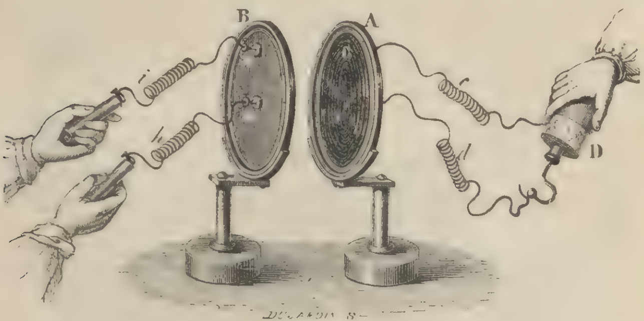


Fig. 658.

a thick layer of shellac varnish, a condition necessary in experimenting with statical electricity, which is always more difficult to insulate than that of the voltaic current, in consequence of its greater tension.

In order to show the production of the induced current by the discharge of a Leyden jar, one end of the wire C is connected with the outer coating, and the other end with the knob of the Leyden jar, as shown in the figure. When the spark passes, the electricity traversing the wire C acts by induction on the neutral fluid of the wire on the plate B, and produces an instantaneous current in this wire. A person holding two copper handles connecting with the wires *i* and *h*, receives a shock, the intensity of which is greater in proportion as the plates A and B are nearer. This experiment proves that frictional electricity can give rise to induced currents as well as voltaic electricity.

The above apparatus can also be used to show the production of induced currents by the influence of voltaic currents. For this purpose the current of a battery is passed through the inducing wire C, while the ends of the other wire, *h* and *i*, are connected with a galvanometer. At the moment at which the current commences or finishes, or when the distance of the two conductors is varied, the same phenomena are observed as in the case of the apparatus (797).

801. **Induction by magnets.**—It has been seen that the influence of a current magnetises a steel bar; in like manner a magnet can produce induced currents in metallic circuits. Faraday has shown this by means of a coil with a single wire of 200 to 300 yards in length. The two extremities of the wire being connected with a galvanometer, as shown in fig. 659, a strongly magnetised bar is suddenly inserted in the bobbin, and the following phenomena are observed:—

i. At the moment at which the magnet is introduced, the galvanometer indicates in the wire the existence of a current, the direction of which is opposed to that which circulates round the magnet, considering the latter as a solenoid on Ampère's theory (784).

ii. When the bar is withdrawn, the needle of the galvanometer, which has returned to zero, indicates the existence of a direct current.

The inductive action of magnets may also be illustrated by the following

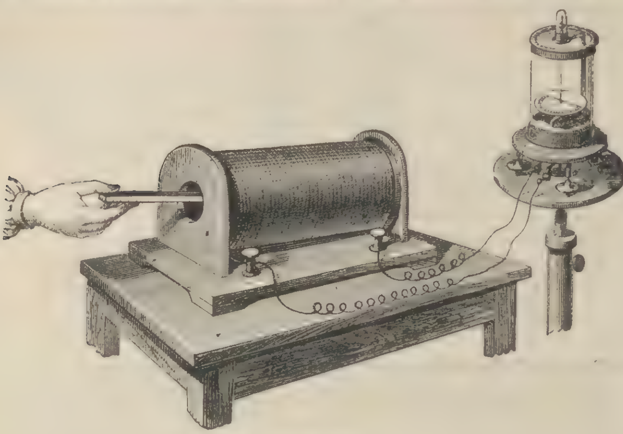


Fig. 659.

experiment: a bar of soft iron is placed in the above bobbin and a strong magnet suddenly brought in contact with it; the needle of the galvanometer is deflected, but returns to zero when the magnet is stationary, and is deflected in the opposite direction when it is removed. The induction is here produced by the magnetisation of the soft iron bar in the interior of the bobbin under the influence of the magnet.

The same inductive effects are produced in the wires of an electromagnet, if a streng magnet be made to rotate rapidly in front of the extremities of the wire in such a manner that its poles act successively by influence on the two branches of the electromagnet: or also by forming two coils round a horse-shoe magnet, and passing a plate of soft iron rapidly in front of the poles of the magnet; the soft iron becoming magnetic reacts by influence on the magnet, and induced currents are produced in the wire alternately in different directions.

The inductive action of magnets is a striking confirmation of Ampère's theory of magnetism. For as in this theory all magnets are solenoids, all the experiments which have been mentioned may be explained by the inductive action of currents which traverse the surface of magnets; the induction of magnets is in short an induction of currents. And it is a useful exercise to see how on this view the inductive action of magnets falls under Lenz's law (799).

802. **Inductive action of magnets on bodies in motion.**—Arago was the first to observe, in 1824, that the number of oscillations which a magnetised needle makes in a given time, under the influence of the earth's magnetism, is very much lessened by the proximity of certain metallic masses, and especially of copper, which may reduce the number

in a given time from 300 to 4. This observation led Arago in 1825 to an equally unexpected fact; that of the rotative action which a plate of copper in motion exercises on a magnet.

This phenomenon may be shown by means of the apparatus represented in fig. 660. It consists of a copper disc, M, moveable about a vertical axis. On this axis is a sheave, B, round which is coiled an endless cord

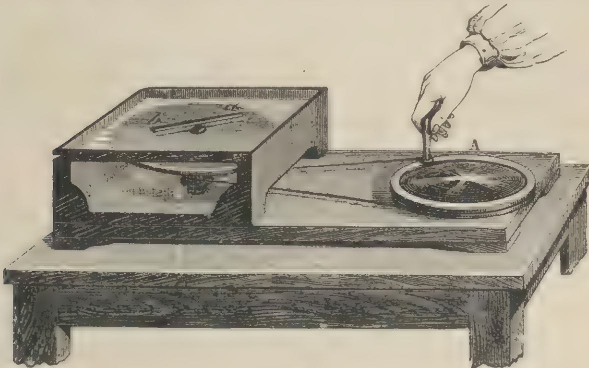


Fig. 660.

passing also round the sheave A. By turning this with the hand, the disc M may be rotated with great rapidity. Above the disc is a glass plate, on which is a small pivot supporting a magnetic needle, *ab*. If the disc be now moved with a slow and uniform velocity, the needle is deflected in the direction of the motion, and stops from 20° to 30° out of the direction of the magnetic meridian, according to the velocity of the rotation of the disc. But if this velocity increases, the needle is ultimately deflected more than 90°; it is then carried along, describes an entire revolution, and follows the motion of the disc until this stops.

Babbage and Herschel modified Arago's experiment by causing a horseshoe magnet placed vertically to rotate below a copper disc suspended on silk threads without torsion; the disc rotated in the same direction as the magnets.

The effect decreases with the distance of the disc, and varies with its nature. The maximum effect is produced with metals; with wood, glass, water, etc. it disappears. Babbage and Herschel have found that representing this action on copper at 100, the action on other metals is as follows: zinc 95, tin 46, lead 25, antimony 9, bismuth 2. Lastly, the effect is enfeebled if the disc presents breaks in the continuity, especially in the direction of the radii; but the same physicists have observed, that it virtually regains the same intensity if these breaks have been soldered with any metal.

Faraday made an experiment the reverse of Arago's first observation; since the presence of a metal at rest stops the oscillations of a magnetic needle, the neighbourhood of a magnet at rest ought to stop the motion

of a rotating mass of metal. Faraday suspended a cube of copper to a twisted thread, which was placed between the poles of a powerful electromagnet. When the thread was left to itself it began to spin round with great velocity, but stopped the moment a powerful current passed through the electromagnet.

Faraday was the first to give an explanation of all these phenomena of magnetism by rotation. They depend on the circumstance that a magnet or a solenoid can induce currents in a solid mass of metal. In the above case the magnet induces currents in the disc, when the latter is rotated; and conversely when the magnet is rotated while the disc is primarily at rest. Now these induced currents by their electrodynamic action tend to destroy the motion which gave rise to them; they are simple illustrations of Lenz's law; they act just in the same way as friction would do.

i. For instance, let AB (fig. 661) be a needle oscillating over a copper disc, and suppose that in one of its oscillations it goes in the direction of the arrows from N to M. In approaching the point M, for instance, it developes there a current in the opposite direction, and which therefore repels it; in moving away from N it produces currents which are of the same kind, and which therefore attract, and both these actions concur in bringing it to rest.

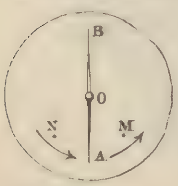


Fig. 661.

ii. Suppose the metallic mass turns from N towards M, and that the magnet is fixed; the magnet will repel by induction points such as N which are approaching A, and will attract M which is moving away; hence the motion of the metal stops, as in Faraday's experiment.

iii. If in Arago's experiment the disc is moving from N to M; N approaches A and repels it while M moving away attracts it; hence it moves in the same direction as the disc.

If this explanation is true all circumstances which favour induction will increase the dynamic reaction; and those which diminish the former will also lessen the latter. We know that induction is greater in good conductors, and that it does not take place in insulating substances; but we have seen that the needle is moved with a force which is less, the less the conducting powers of the disc, and it is not moved when the disc is of glass. Dove has found that there is no induction on a tube split lengthwise in which a coil is introduced.

In order to bring the oscillations of the needle of a galvanometer more quickly to rest, the wire is coiled upon a copper frame. Such an arrangement is called a *damper*, and in practice it is frequently used.

803. **Induction by the action of the earth.**—Faraday discovered that terrestrial magnetism can develope induced currents in metallic bodies in motion, acting like a powerful magnet placed in the interior of the earth in the direction of the dipping needle, or, according to the theory of Ampère, like a series of electrical currents directed from east to west parallel to the magnetic equator. He first proved this by placing

a long helix of copper wire covered with silk in the plane of the magnetic meridian parallel to the dipping needle; by turning this helix 180° round an axis perpendicular to its length in its middle, he observed that at each turn a galvanometer connected with the two ends of the helix was deflected. The apparatus depicted in fig. 662, and known as *Delezenne's*

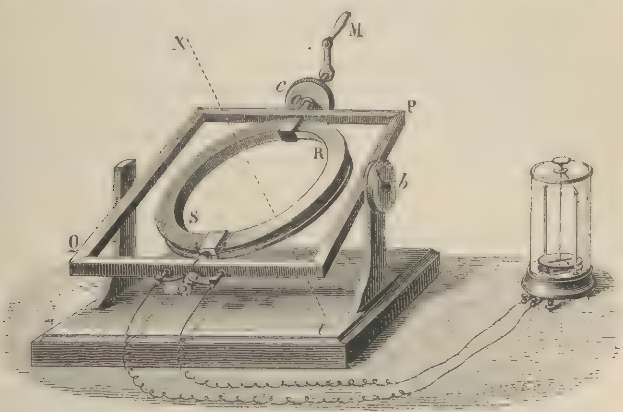


Fig. 662.

circle, serves for showing the existence of terrestrial induced currents. It consists of a wooden ring, RS, about two feet in diameter, fixed to an axis *oi*, about which it can be turned by means of a handle, M. The axis *oi* is itself fixed in a frame, PQ, moveable about a horizontal axis. By needles fixed to these two axes the inclination towards the horizon of the frame PQ and therefore of the axis, *oa*, is indicated on a dial, *b*, while a second dial, *c*, gives the angular displacement of the ring. This ring has a groove, in which is coiled a large quantity of insulated copper wire. The two ends of the wire terminate in a *commutator* analogous to that in Clarke's apparatus (809), the object of which is to pass the current always in the same sense, although its direction, SR, changes at each semi-revolution of the ring. On each of the rings of the commutator are two brass plates, which successively transmit the current to two wires in contact with the galvanometer. The axis *oa* being in the magnetic meridian, and the ring RS at right angles to the direction XY of the dipping needle, if it is slowly rotated the needle of the galvanometer is deflected, and by its deflection indicates in the wire coiled on the ring an induced current whose intensity increases until it has been turned through 90°; the deviation then decreases, and is zero when the ring has made a semi-revolution. If the rotation continues the current reappears but in a contrary direction, and attains a second maximum at 270°; becoming null again after a complete turn. When the axis *oa* is parallel to the dip there is no current.

804. **Induction of a current on itself. Extra current.**—If a closed circuit traversed by a voltaic current be opened, a scarcely perceptible

spark is obtained, if the wire joining the two poles be short. Further, if the observer himself form part of the circuit by holding a pole in each hand, no shock is perceived unless the current is very intense. If, on the contrary, the wire is long, and especially if it makes a great number of turns, so as to form a bobbin with very close folds, the spark, which is inappreciable when the current is closed, acquires a great intensity when it is opened, and an observer in the circuit receives a shock which is the stronger the greater the number of turns.

Faraday has referred this strengthening of the current when it is broken to an inductive action which the current in each coil exerts upon the adjacent coils : an action in virtue of which there is produced in the bobbin a direct induced current, that is, one in the same direction as the principal one. This is known as the *extra current.*

To show the existence of this current, at the moment of opening Faraday has arranged the experiment as seen in fig. 663. Two wires from the

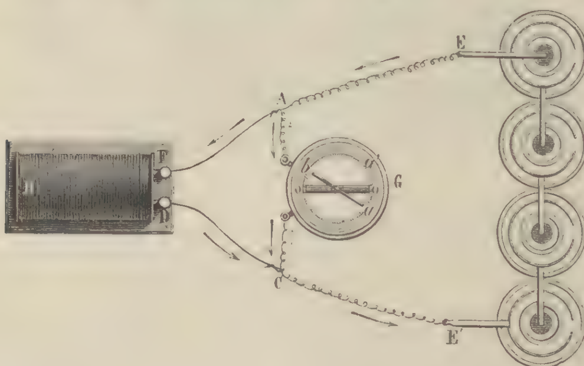


Fig. 663.

poles of a battery are connected with two binding screws D and F, with which are also connected the two ends of a bobbin B with a long fine wire. On the path of the wires at the points A and C are two other wires which are connected with a galvanometer G. Hence the current from the pole E branches at A into two currents, one which traverses the galvanometer, the other the bobbin, and both joining the negative pole E′.

The needle of the galvanometer being then deflected by the current which goes from A to C, it is brought back to zero, and kept there by an obstacle which prevents it from turning in the direction G*a*, but leaves it free in the opposite direction. On breaking contact at E, it is seen that the moment the circuit is open the needle is deflected in the direction G*a′*; showing a current contrary to that which passed during the existence of the current, that is, showing a current from C to A. But the battery current having ceased, the only remaining one is the current AFBDCA, and since in the part CA the current goes from C to A, it

must traverse the entire circuit in the direction AFBDC, that is the same as the principal current. This current, which thus appears when the circuit is opened, is the *extra current.*

805. **Extra current on opening and on closing.**—The coils of the spiral act inductively on each other, not merely on opening but also on closing the current. Here in accordance with the general law of induction, each spire acting on each succeeding one induces a current in the opposite direction to its own, that is an inverse current; this, which is the *extra current on closing*, or the *inverse extra current*, being of contrary direction to the principal one, diminishes its intensity, and lessens or suppresses the spark on closing.

When, however, the current is opened, each spire then acts inductively on each succeeding one, producing a current in the same direction as its own, and which therefore greatly heightens the intensity of the principal current. This is the extra current on opening, or *direct extra current.*

To observe the direct extra current, the conductor on which its effect is to be traced may be introduced into the circuit, by being connected in any suitable manner with the binding screws A and C in the place of the galvanometer.

It can thus be shown that the direct extra current gives violent shocks, bright sparks, decomposes water, melts platinum wire, and magnetises steel needles. Abria has found that the intensity of the extra current is about 0·72 of the principal current. The shock produced by the current may be tried by attaching the ends of the wire to two files, which are held in the hands. On moving the point of one file over the teeth of the other a series of shocks is obtained, due to the alternate opening and closing of the current.

The above effects acquire greater intensity when a bar of soft iron is introduced into the bobbin, or, what is the same thing, when the current is passed through the bobbin of an electromagnet; and still more is this the case if the core, instead of being massive, consists of a bundle of straight wires. Faraday explains this strengthening action of soft iron as follows: If inside the spiral there is an iron bar, when on opening the circuit the principal current disappears, the magnetism which it evokes in the bar disappears too; but the disappearance of this magnetism acts like the disappearance of the electrical current, the disappearing magnetism induces a current in the same direction as the disappearing principal current, the effect of which is thus heightened.

In the experiments just described the effects of the two extra currents accompany those of the principal current. Edlund has devised an ingenious arrangement of apparatus by which the action of the principal current on the measuring instruments can be completely avoided, so that only that of the extra current remains. In this way he has arrived at the following laws:

i. *The intensity of the currents used being the same, the extra-currents obtained on opening and closing have the same electromotive force.*

ii. *The electromotive force of the extra-current is proportional to the intensity of the primary current.*

806. **Induced currents of different orders.**—Spite of their instantaneous character, induced currents can themselves, by their action on closed circuits, give rise to new induced currents, these again to others, and so on, producing *induced currents of different orders.*

These currents, discovered by Henry, may be obtained by causing to act on each other a series of bobbins, each formed of a copper wire covered with silk, and coiled spirally in one plane, like that represented in the plate A, in fig. 657. The currents thus produced are alternately in opposite directions, and their intensity decreases in proportion as they are of a higher order.

807. **Properties of induced currents.**—Notwithstanding their instantaneous character, it appears from the preceding experiments that induced currents have all the properties of ordinary currents. They produce violent physiological, luminous, calorific, and chemical effects, and finally give rise to new induced currents. They also deflect the magnetic needle, and magnetise steel bars when they are passed through a copper wire coiled in a helix round the bars.

The intensity of the shock produced by induced currents renders their effects comparable to those of electricity in a state of tension. But as they act on the galvanometer the electricity is present, both in a state of tension and in the dynamical condition.

The direct induced current and the inverse induced current have been compared as to three of their actions: the violence of the shock, the deflection of the galvanometer, and the magnetising action on steel bars. In these respects they differ greatly: they are about equal in their action on the galvanometer; but while the shock of the direct current is very powerful, that of the inverse current is scarcely perceptible. The same difference prevails with reference to the magnetising force. The direct current magnetises to saturation, while the inverse current does not magnetise.

808. **Laws of induced currents.**—In his special treatise on induction, Matteucci has deduced from his own researches, and from those of Faraday, Lenz, Dove, Abria, Weber, Marianini, and Felici, the following laws in reference to induced currents :

i. *The intensity of induced currents is proportional to that of the inducing currents.*

ii. *This intensity is proportional to the product of the length of the inducing and induced currents.*

iii. *The electromotive force developed by a given quantity of electricity is the same whatever be the nature, section, or shape of the inducing circuit.*

iv. *The electromotive force developed by the induction of a current on any given conducting circuit is independent of the nature of the conductor.*

v. *The development of induction is independent of the nature of the insulating body interposed between the induced and inducing circuit.*

This latter law is in disaccord with the experiments of Faraday, on the induction of statical electricity (673).

APPARATUS FOUNDED ON INDUCTION.

809. **Magneto-electrical apparatus.**—After the discovery of magneto-electrical induction, several attempts were made to produce an uninterrupted series of sparks by means of a magnet. Apparatus for this purpose were devised by Pixii and Ritchie, and subsequently by Saxton, Ettingshausen, and Clarke. Fig. 664 represents that invented by Clarke. It consists of a powerful horse-shoe magnetic battery, A, fixed against a

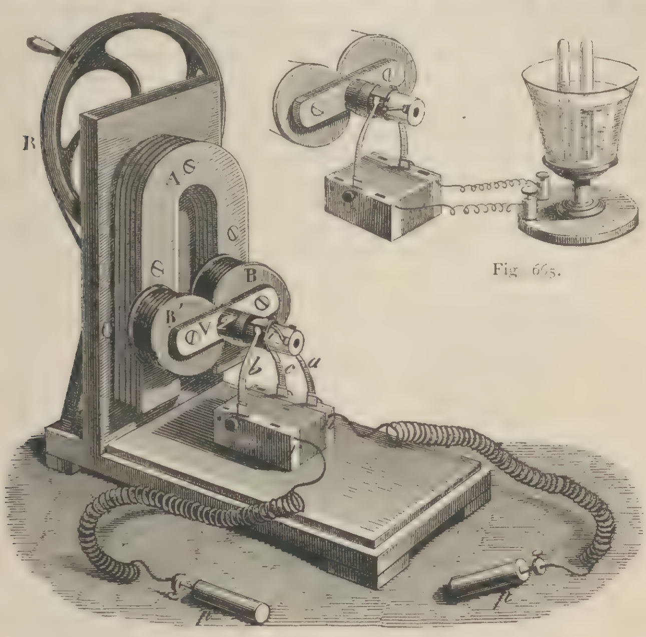


Fig. 665.

Fig. 664.

vertical wooden support. In front of this there are two bobbins BB′, moveable round a horizontal axis. These bobbins are coiled on two cylinders of soft iron joined at one end by a plate of soft iron, V, and at the other by a similar plate of brass. These two plates are fixed on a copper axis, terminated at one end by a commutator, *qi*, and at the other by a pulley, which is moved by an endless band passing round a large wheel, which is turned by a handle.

Each bobbin consists of about 1,500 turns of very fine copper wire covered with silk. One end of the wire of the bobbin B is connected on the axis of rotation with one end of the wire of the bobbin B′, and the two other ends of these wires terminate in a copper ferrule or washer, *q*, which is fixed to the axis, but is insulated by a cylindrical envelope of

ivory. In order that in each wire the induced current may be in the same direction, it is coiled on the two bobbins in different directions, that is, one is right-handed, the other left-handed.

When now the electromagnet turns, its two branches become alternately magnetised in contrary directions under the influence of the magnet A, and in each wire an induced current is produced, the direction of which changes at each half turn.

Let us follow one of the bobbins, B for instance, while it makes a complete revolution in front of the poles a and b of the magnet; calling the poles of the electromagnet successively a' and b'. Let us further consider the latter when it passes in front of the north pole of the magnetic battery (fig. 666). The iron has then a south pole in which, as we know, the Ampèrian currents move like the hands of a watch. The contrary seems to be represented by fig. 666, but it must be remembered that the bobbins are seen here as they are in fig. 664; and hence it is, when viewed at the end which grazes the magnet, that the Ampèrian currents seem to turn like the hands of a watch. These currents act inductively on the wire of the bobbin, producing a current in the same direction (799, iii.), for the bobbin moves away from the pole a, its soft iron is demagnetised, and

Fig. 666.

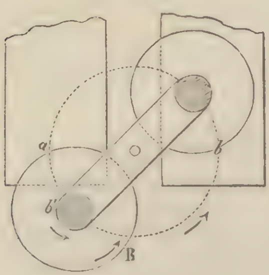
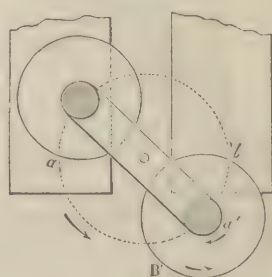


Fig. 667.



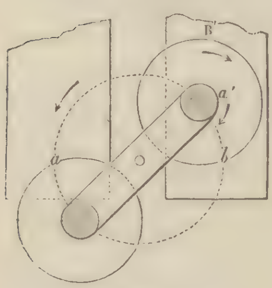


Fig. 668.

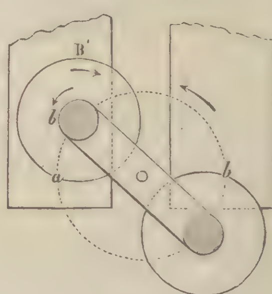


Fig. 669.

the Ampèrian currents cease (799). The intensity of the induced current in the bobbin decreases, until the right line joining the axes of the

two bobbins is perpendicular to that which joins the poles *a* and *b* of the bar. There is now no magnetism in the bar, but quickly approaching the pole *b*, its soft iron is then magnetised in the opposite direction, that is, it becomes a north pole (fig. 667). The Ampèrian currents are then in the direction of the arrow *a′*; and as they are commencing, they develope in the wire of the bobbin an inverse current (799), which is in the same direction as that developed in the first quarter of the revolution. Moreover, this second current adds itself to the first, for while the bobbin moves away from *a*, it approaches *b*. Hence, during the lower half revolution from *a* to *b*, the wire was successively traversed by two induced currents in the same direction, and if the rotatory motion is sufficiently rapid, we might admit during this half revolution the existence of a single current of the wire.

The same reasoning applied to the figures 668 and 669 will show that during the upper half revolution the wire of the bobbin B is still traversed by a single current, but in the opposite direction to that of the lower half revolution. What has been said about the bobbin B applies obviously to the bobbin B′; yet as one of these is right-handed and the other left-handed, during each upper or lower half revolution the currents are constantly in the same direction in the two bobbins. At each successive half revolution they both change, but are in the same direction as regards each other; the term direction having here reference to figs. 666–669.

810. **Commutator.**—The object of this apparatus (fig. 670), of which fig. 671 is a section, is to bring the two alternative currents always in the

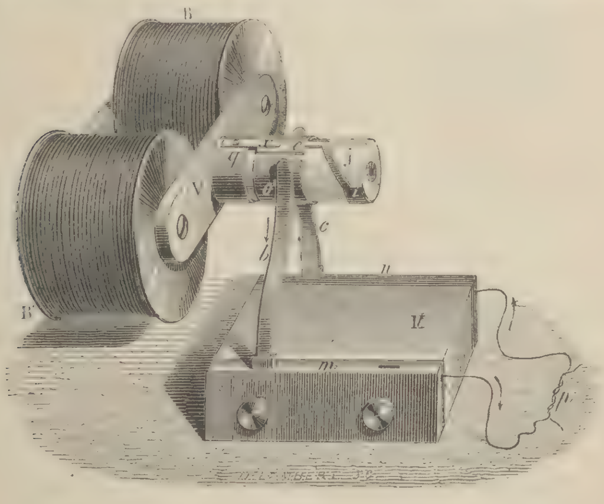


Fig. 670.

same direction. It consists of an insulating cylinder of ivory or ebony, J, in the axis of which is a copper cylinder K, of smaller diameter, fixed to

the armature, V, and turning with the bobbins. On the ivory cylinder is first a brass ferrule, *q*, and in front of it two half ferrules, *o* and *o′* also of brass and completely insulated from one another. The half ferrule *o′* is connected with the ferrule *q* by a tongue *x*. On the sides of a block of wood, M, there are two brass plates, *m n*, on which are screwed two elastic springs, *b* and *c*, which press successively on the half ferrules *o* and *o′*, when rotation takes place.

We have already seen that the two ends of the wire of the bobbin, those in the same direction with respect to the currents passing through them at any time, which will be found to be those farthest away from the armature V, terminate in the metallic axis *k*, and therefore on the half ferrule *o′*; while the other two ends, both in the same direction with respect to the current, are joined to the ferrule *q*, and therefore to the half ferrule *o*. It follows that the pieces *o o′* are constantly poles of alternating currents which are developed in the bobbins, and as these are alternately in contrary directions, the pieces *o* and *o′* are alternately positive and negative. Now taking the case in which the half ferrule *o′* is positive, the current descends by the spring *b*, follows the plate *m*, arrives at *n* by the joining wire *p*, ascends in *c*, and is closed by contact with the piece *o*; then when in consequence of rotation *o* takes the place of *o′*, the current retains the same direction, for, as it is then reversed in the bobbins, *o* has become positive, and *o′* negative, and so forth as long as the bobbin is turned.

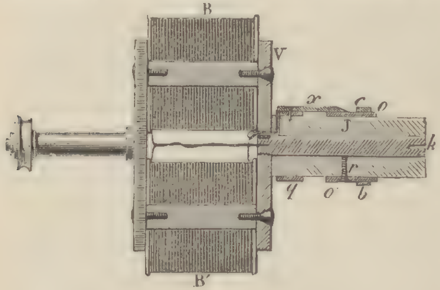


Fig. 671.

With the two springs *b* and *c* alone, the opposite currents from the two pieces *o* and *o′* could not unite, when *m* and *n* are not joined; this is effected by means of a third spring, *a* (fig. 664), and of two appendices, *i*, only one of which is visible in the figure. These two pieces are insulated from one another on an ivory cylinder, but communicate respectively with the pieces *o* and *o′*. As often as the spring *a* touches one of these pieces it is connected with the spring *b*, and the current is closed, for it passes from *b* to *a*, and then reaches the spring *c* by the plate *n*. On the contrary, as long as the spring *a* does not touch one of these appendices the current is broken.

For physiological effects the use of the spring *a* greatly increases the intensity of the shocks. For this purpose two long spirals of copper wire with handles, *p* and *p′*, are fixed at *n* and *m*. Holding the handles in the hands so long as the spring *a* does not touch the appendices *i*, the current passes through the body of the experimenter, but without appreciable effect; while each time that the plate *a* touches one of the appendices *i*, the current, as we have seen above, is closed by the pieces *b*, *a*,

and *c*, and ceasing then to pass through the wires *np*, *mp'*, there is produced in this and through the body a direct extra current which produces a violent shock.

This is renewed at each semi-revolution of the electromagnet, and its intensity increases with the velocity of the rotation. The muscles contract with such force that they do not obey the will, and the two hands cannot be detached. With a well-constructed apparatus of large dimensions a continuance of the shock is unendurable; the person receiving it is prostrated, rolls on the ground, and is soon completely at the mercy of the operator.

All the effects of voltaic currents may be produced by the induced currents of Clarke's machine. Figure 665 shows how the apparatus is to be arranged for the decomposition of water. The spring *a* is suppressed, the current being closed by the two wires which represent the electrodes.

For physiological and chemical effects, the wire rolled on the bobbins is fine, and each about 500 to 600 yards in length. For physical effects, on the contrary, the wire is thick, and there are about 25 to 35 yards on each bobbin. Figures 672 and 673 represent the arrangement of the bobbins and the commutator in each case. The first represents the inflammation of ether, and the second the incandescence of a metallic wire,

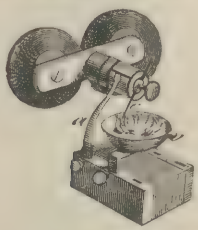


Fig. 672.

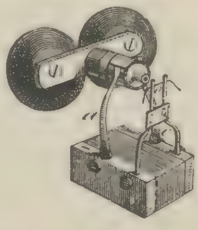


Fig. 673.

o, in which the current from the plate *a*, to the plate *c*, always passes in the same direction.

Pixii's and Saxton's electromagnetic machine differs from Clarke's in having the electromagnet fixed while the magnet rotates.

Wheatstone has recently devised a compendious form of the magneto-electrical machine, for the purpose of using the induced spark in firing mines (716).

811. **Magneto-electrical machine.**—The principle of Clarke's apparatus has received in the last few years a remarkable extension in large magneto-electrical machines, by means of which mechanical work is transformed into powerful electric currents by the inductive action of magnets on bobbins in motion.

The first machine of this kind was invented by Nollet, in Brussels, in 1850; this has been greatly improved by Van Malderen, who has also applied it to electrical illumination.

This machine is represented in fig. 674, as it stands in a workshop at the Hôtel des Invalides, in Paris, where it was constructed. One of

these machines was exhibited in the International Exhibition of 1862. It consists of a cast iron frame, $5\frac{1}{2}$ feet in height, on the circumference of

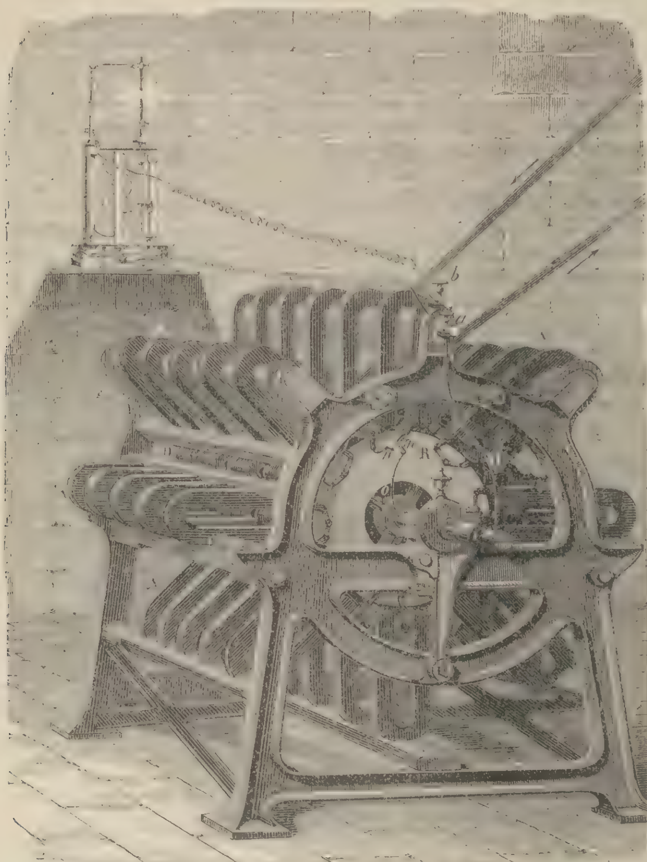


Fig. 674.

which 8 series of five powerful horse-shoe magnetic batteries, A, A, A .. are arranged in a parallel order on wooden cross-pieces. These batteries, each of which can support from 120 to 130 pounds, are so arranged, that if they are considered either parallel to the axis of the frame, or in a plane perpendicular to this axis, opposite poles always face one another. In each series, the outside batteries consist of three magnetised plates, while the three middle ones have six plates, because they act by both faces, while the first only acts by one.

On a horizontal iron axis going from one end to the other of the frame

four bronze wheels are fixed, each corresponding to the intervals between the magnetic batteries of two vertical series. There are 16 bobbins on the circumference of each of these, that is, as many as there are magnetic poles in each vertical series of magnets. These bobbins, represented in figure 676, differ from those of Clarke's apparatus in having, instead of a single wire, 12 wires each, 11½ yards in length, by which the resistance is diminished. The coils of these bobbins are insulated by means of bitumen dissolved in oil of turpentine. These are not rolled upon solid cylinders of iron, but on two iron tubes, slit longitudinally ; this device renders the magnetisation and demagnetisation more rapid when the bobbins pass in front of the poles of the magnet. Further, the discs of copper which terminate the bobbins are divided in the direction of the radius, in order to prevent the formation of induced currents in these discs. The four wheels being respectively provided with 16 bobbins each, there are altogether 64 bobbins arranged in 16 horizontal series of four, as seen at D, on the left of the frame. The length of the wire on each bobbin being 12 times 11½ yards, or 138 yards, the total length in the whole apparatus is 64 times 138 yards, or 8,832 yards.

The wires are coiled on all the bobbins in the same direction, and not only on the same wheel, but on all four, all wires are connected with one another. For this purpose the bobbins are joined, as shown in figure 675 ; on the first wheel the twelve wires of the first bobbin, *x*, are connected on a piece of mahogany fixed on the front face of the wheel with a plate of copper, *m*, connected by a wire, O, with the centre of the axis

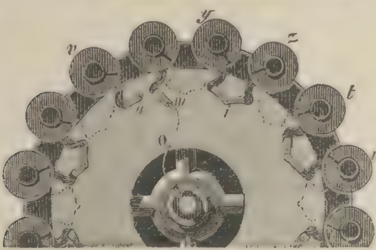


Fig. 675.

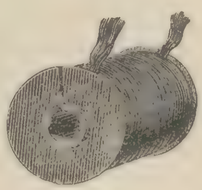


Fig. 676.

which supports the wheels. At the other end on the other face of the wheel, the same wires are soldered to a plate indicated by a dotted line which connects them with the bobbin *y* ; from this they are connected with the bobbin *z* by a plate *i*, and so on, for the bobbins *t*, *u* . . . up to the last, *v*. The wires of this bobbin terminate in a plate, *n*, which traverses the first wheel, and is soldered to the wires of the first bobbin of the next wheel, on which the same series of connections is repeated ; these wires pass to the third wheel, thence to the fourth, and so on, to the end of the axis.

The bobbins being thus arranged, one after another, like the elements of a battery connected in a series (743), the electricity has a high tension. But the bobbins may also be arranged by connecting the plates alternately,

not with each other, but with two metal rings, in such a manner that all the ends of the same name are connected with the same ring. Each of these rings is then a pole, and this arrangement may be used where a high degree of tension is not required.

From these explanations it will be easy to understand the manner in which electricity is produced and propagated in this apparatus. An endless band receiving its motion from a steam engine passes round a pulley fixed at the end of the axis which supports the wheels and the bobbins, and moves the whole system with any desired rapidity. Experience has shown that to obtain the greatest degree of light, the most suitable velocity is 235 revolutions in a minute. During this rotation, if we at first consider a single bobbin, the tube of soft iron on which it is coiled, in passing in front of the poles of the magnet, undergoes at its two ends an opposite induction, the effects of which are added, but change from one pole to another. As these tubes, during one rotation, pass successively in front of sixteen poles alternately of different names, they are magnetised eight times in one direction, and eight times in the opposite direction. In the same time there are thus produced in the bobbin eight direct induced currents, and eight inverse induced currents; in all, sixteen currents in each revolution. With a velocity of 235 turns in a minute, the number of currents in the same time is $235 \times 16 = 3760$ alternately in opposite directions. The same phenomenon is produced with each of the 64 bobbins: but as they are all coiled in the same direction, and are connected with each other, their effects accumulate, and there is the same number of currents, but they are more intense.

To utilise these currents in producing an intense electric light, the communications are made as shown in figure 677. On the posterior side the last bobbin, *x′*, of the fourth wheel terminates by a wire, G, on the axis MN, which supports the wheels: the current is thus conducted to the axis, and thence over all the machine, so that it can be taken from any desired point. In the front the first bobbin, *x*, of the first wheel communicates by the wire O, not with the axis itself, but with a steel

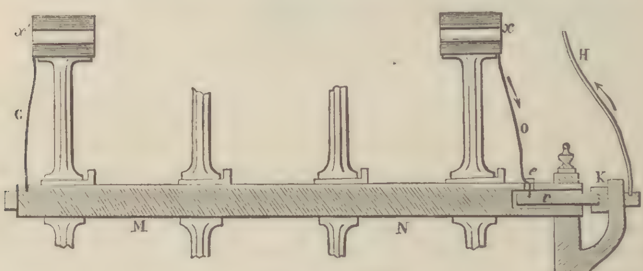


Fig. 677.

cylinder, *c*, fitted in the axis, from which, however, it is insulated by an ivory collar. The screw *e*, to which the wire O is attached, is likewise

insulated by a piece of ivory. From the cylinder *c* the current passes to a fixed metallic piece, K, from which it passes to the wire H, which transmits it to the binding screw, *a*, of fig. 674. The binding screw *b* communicates with the framework, and therefore with the wire of the last bobbin, x' (fig. 677). From the two binding screws, *a* and *b*, the current is conducted by means of two copper wires to two charcoals, the distance of which is regulated by means of an apparatus analogous in principle to that already described (748).

In this machine the currents are not rectified so as to be in the same direction ; hence each carbon is alternately positive and negative, and in fact they are consumed with equal rapidity. Experiment has shown that when these currents are applied to produce the electric light, it is not necessary they should be in the same direction ; but when they are to be used for electrometallurgy, or for magnetising, they must be rectified, which is effected by means of a suitable commutator.

The light produced by the magneto-electrical machine is very intense ; with a machine of four wheels the light obtained is equal to that of 150 Carcel lamps. A machine of six wheels gives a light equal to 200 Carcel lamps.

Serrin has constructed a new regulator for this light, which, like the older ones, brings the charcoals together in proportion as they become used ; and further removes them when they are in contact. It contains no clockwork motion, and is worked by the weight of one of its pieces.

This light, which requires no other expenditure than that of a single horse-power to turn the coils when there are not more than four of them, is advantageously used for signalling by night on large vessels, and for lighthouses.

One of these, constructed by Holmes, is now in use at the South Foreland lighthouse.

812. **Siemens' armature.**—Siemens has devised an armature or bobbin for magneto-electrical machines, in which the insulated wire is wound longitudinally on the core, instead of transversely, as is usually the case.

It consists of a soft iron cylinder AB (fig. 678) from one foot to three feet in length, according to circumstances.

A deep grove is cut on the outer length of this core and on the ends, in

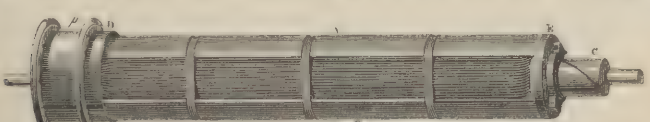


Fig. 678.

which is coiled the insulated wire as in a multiplier, To the two ends of the cylinder brass discs E and D are secured. With E is connected a commutator C, consisting of two pieces of steel insulated from each other and connected respectively with the two ends of the wire. On the other

disc is a pulley, round which passes a cord, so that the bobbin moves very rapidly on the two pivots.

When a voltaic current circulates in the wire, the two cylindrical segments, A and B, are immediately magnetised, one with one polarity and the other with the opposite. On the other hand, if, instead of passing a voltaic current through the wire of the bobbin, the bobbin itself be made to rotate rapidly between the opposite poles of magnetised masses, as the segments A and B become alternately magnetised and demagnetised, their induction produces in the wire a series of currents alternately positive and negative, as in Clarke's apparatus (809). When these currents are collected in a commutator which adjusts them, that is, sends all the positive currents on one spring and all the negative on another, these springs become electrodes, from one of which positive electricity starts and from the other negative. If these springs are connected by a conductor, the same effects are obtained as when the two poles of a battery are united.

Siemens has constructed magneto-electrical machines in which this armature is utilised. It has the great advantage that a large number of small magnets may be used instead of one large one. As, weight for weight, the former possesses greater magnetic force than the latter, they can be made more economically. And as the armature is always very near the magnets it receives greater momentum, and is more rapidly changed.

813. **Wild's magneto-electrical machine.**—Mr. Wild has recently constructed a magneto-electrical machine, in which Siemens' armature is used along with a new principle—that of the multiplication of the current. Instead of utilising directly the current produced by the induction of a magnet, Mr. Wild passes it into a strong electromagnet, and by the induction of this latter a more energetic current is obtained.

This machine consists first of a battery of 12 to 16 magnets, each of which weighs about 3 pounds, and can support about 20 pounds. Between the poles of the magnets two soft iron keepers CC are arranged, separated by a brass plate O. These three pieces are joined by bolts, and the whole compound keeper is perforated longitudinally by a cylindrical cavity, in which works a Siemens' armature *n*, about 2 inches in diameter. The wire of this armature terminates in a commutator, which leads the positive and negative currents to two binding screws, *a* and *b*. This commutator is represented on a larger scale in figure 681. At the other end is a pulley by which the armature can be turned at the rate of 25 turns in a second. The wire on the armature is 20 yards long.

Below the support for the magnets and their armatures are two large electromagnets BB. Each consists of a rectangular soft iron plate, 36 inches in length by 26 in breadth and $1\frac{1}{4}$ inch thick, on which are coiled about 1,600 feet of insulated copper wire. The wires of these electromagnets are joined at one end, so as to form a single circuit of 3,200 feet. One of the other ends is connected with the binding screw *a* and the other with *b*. At the top the two plates are joined by a transverse plate of iron so as to form a single electromagnet.

At the bottom of the electromagnets BB are two iron armatures separated by a brass plate O, and in the entire length is a cylindrical channel in

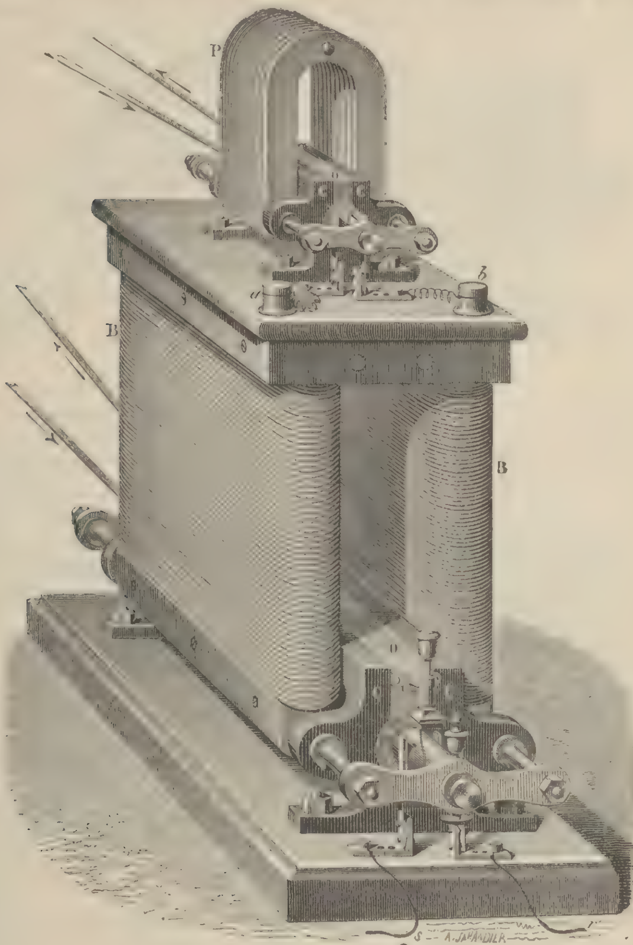


Fig. 679.

which works a Siemens' armature as above; this armature, however, is above a yard in length, nearly 6 inches in diameter, and its wire is 100 feet long. The ends are connected with a commutator, from which the adjusted currents pass to two wires *r* and *s*. The armature *m* is rotated at the rate of 1,700 turns in a minute.

Fig. 680 shows on a larger scale a cross section of the bobbin, *m*, of

the armatures, CC, and of the plates, AA, on which is coiled the wire of the electromagnets BB.

These details being premised, the following is the working of the

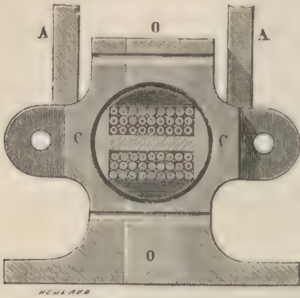


Fig. 680.

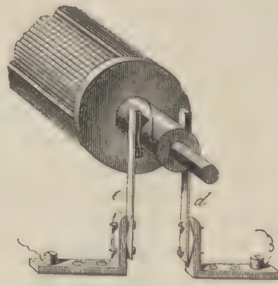


Fig. 681.

machine. When the armatures *n* and *m* are rotated by means of a steam engine with the velocity mentioned, the magnets produce in the first armature induced currents, which, adjusted by the commutator, pass into the electromagnet, BB, and magnetise it. But as these impart to the lower armatures, CC, opposite polarities, the induction of these latter produces in the armature *m*, a series of positive and negative currents far more powerful than those of the upper armature; so that when these are adjusted by a commutator and directed by the wires *r* and *s*, very powerful effects are obtained.

These effects are still further intensified if, as Mr. Wild has done, the adjusted current of the armature, *m*, is passed into a second electric magnet, whose armatures surround a third and larger Siemens' armature turning with the two others. A current is thus obtained which melts an iron wire a foot long and more than 2 inches in diameter.

814. **Ladd's dynamomagnetic machine.**—Mr. Ladd, philosophical instrument maker, in Beak Street, Regent Street, has invented a very remarkable dynamomagnetic machine. It consists of two Siemens' armatures, rotating with great velocity, and of two iron plates AA (fig. 682), surrounded by an insulated copper wire. Ladd's machine differs from that of Wild in the following respects:

1. There are no permanent magnets; 2nd, the electromagnets BB are not joined so as to form a single electromagnet, but are two distinct electromagnets, each having at the end two hollow cylinders, CC′, in which are fitted two Siemens' armatures *m* and *n*; the current of the armature *n* passing round the electromagnets reverts to itself. This reaction of the current upon itself is an essential feature of the machine; it is an application of a principle announced simultaneously by Mr. Wheatstone and by Mr. Siemens. The wire of the armature *m* is independent, and passes into the apparatus which is to utilise the current, for instance two carbon points, D.

The machine being thus arranged, if a voltaic current be passed once for all through the electromagnets BB, it magnetises the plates AA and their keepers, which by their reciprocal action retain a quantity of remanent magnetism sufficient to work the machine. If, then, the armatures *m* and *n* be rotated by means of two bands passing round a common drum, the magnetism of the hollow cylinders CC′ acting upon the armature *n*, excites induction currents, which, adjusted by a commutator, pass round the electromagnets BB, and more strongly magnetise the cylinders or shoes CC′. These in their turn reacting more powerfully on the armature *n*, strengthen the current; we thus see, that *n* and B continually and mutually strengthen each other as the velocity of the rotation increases. Hence as the iron of the armature, *m*, becomes more and more strongly magnetised under the influence of the electromagnets BB, a gradually more intense induced current is developed in this armature,

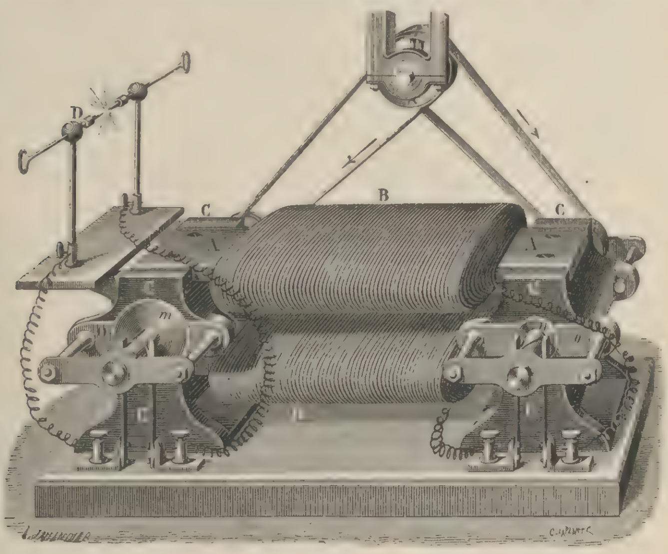


Fig. 682.

which is directed, commutated or not, according to the use for which it is designed.

In a machine which Mr. Ladd exhibited at the Paris Exhibition of 1867 the plates AA were only 24 inches in length by 12 inches in width. With these small dimensions the current is equal to 25 to 30 Bunsen's cells. It can work the electric light and keep incandescent a platinum wire a metre in length and 0·5mm. in diameter.

The above form of the machine is worked by power. Mr. Ladd has devised a more compact form, which may be worked by hand. This is represented in fig. 683. The two armatures are fixed end to end, and

the coils are wound on it at right angles to each other, as shown in the figure. The current from this can raise to white heat 18 inches of platinum wire 0·01 in. thickness, and with an inductorium containing 3 miles of secondary wire 2 in. sparks can be obtained.

Both Ladd's and Wild's machines are liable to the objection of requiring to be rotated at a rapid rate. The armatures become heated by the repeated development of induction currents. This has been remedied by Mr. Ladd, who has introduced into the shoes or hollow cylinders several apertures through which a stream of cold water is made to flow. Before they can be applied industrially, their velocity must be reduced, either by multiplying the number of Siemens' armatures or modifying their arrangement.

These machines furnish a remarkable instance of the transformation of mechanical force into electricity, light and heat (264, 451).

815. **Inductorium. Ruhmkorff's coil.**—These are arrangements for producing induced currents, in which a current is induced by the action of an electric current, whose circuit is alternately opened and closed in rapid succession. These instruments, known as *inductoriums* or *induction*

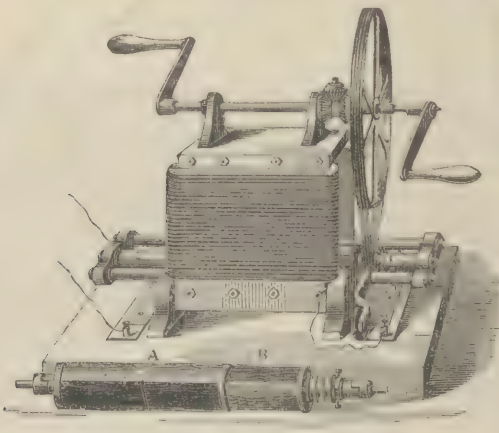


Fig. 683.

coils, present considerable variety in their construction, but all consist essentially of a hollow cylinder in which is a bar of soft iron, or bundle of iron wires, with two helices coiled round it, one connected with the poles of a battery, the current of which is alternately opened and closed by a self-acting arrangement, and the other serving for the development of the induced current. By means of these apparatus, with a current of three or four Grove's cells, physical, chemical, and physiological effects are produced equal to and superior to those obtainable with electrical machines and even the most powerful Leyden batteries.

Of all the forms those constructed by Ruhmkorff are the most powerful.

Fig. 684 is a representation of one, the coil of which is about 14 inches in length. The *primary* or *inducing* wire is of copper, and is about 2mm. in diameter, and 40 or 50 yards in length. It is coiled directly on a cylinder of cardboard, which forms the nucleus of the apparatus, and is enclosed in an insulating cylinder of glass, or of caoutchouc. On these is coiled the secondary or induced wire, which is also of copper, and is about $\frac{1}{3}$mm. in diameter. A great point in these apparatus is the insulation. The wires are not merely insulated by being in the first case covered with silk, but each individual coil is separated from the rest by a layer of melted shellac. The length of the secondary wire varies greatly;

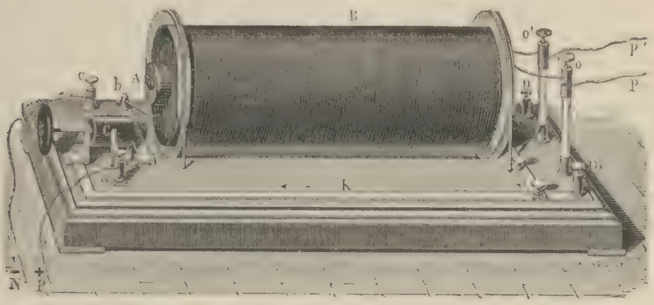


Fig. 684.

in some of Ruhmkorff's largest sizes it is as much as 60 miles. With these great lengths the wire is thinner, about $\frac{1}{4}$mm. The thinner the wire the greater the *tension* of the induced electricity.

The following is the working of the apparatus. The current arriving by the wire P at a binding screw, *a*, passes thence into the commutator, C, to be afterwards described (fig. 686), thence by the binding screw, *b*, it enters the primary wire, where it acts inductively on the secondary wire; having traversed the primary wire it emerges by the wire *s* (fig. 685). Following the direction of the arrows, it will be seen that the current ascends in the binding screw, *i*, reaches an oscillating piece of iron, *o*, called the *hammer*, descends by the *anvil*, *h*, and passes into a copper plate, K, which takes it to the commutator, C. It goes from there to the binding screw, *c*, and finally to the negative pole of the battery by the wire N.

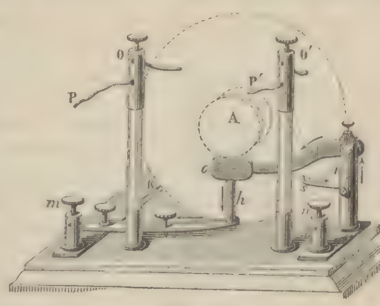


Fig. 685.

The current in the primary wire only acts inductively on the secondary wire (797), when it opens or closes, and hence must be constantly interrupted. This is effected by means of the oscillating

hammer o (fig. 685). In the centre of the bobbin is a bundle of soft iron wires, forming together a cylinder a little longer than the bobbin, and thus projecting at the end as seen at A. When the current passes in the primary wire, this hammer o is attracted; but, immediately, there being no contact between o and h, the current is broken, the magnetisation ceases, and the hammer falls; the current again passing, the same series of phenomena recommences, so that the hammer oscillates with great rapidity.

816. **Condenser.**—In proportion as the current passes thus intermittently in the primary wire of the bobbin, at each interruption an induced current, alternately direct and inverse, is produced in the secondary wire. But as this is perfectly insulated, the induced current acquires such an intensity as to produce very powerful effects. Fizeau has increased this intensity still more by interposing a condenser in the primary circuit. As constructed by Ruhmkorff for his largest apparatus, this consists of 150 sheets of tinfoil about 18 inches square, so that the total surface is about 75 square yards. These sheets being joined are fastened on two sides of a band of oiled silk, which insulates them, forming thus two coatings; they are then coiled several times round each other, another band of silk being interposed, so that the whole can be placed below the helix in the base of the apparatus. One of these coatings, the positive, is connected with the binding screw, i, which receives the current on emerging from the bobbin; and the other, the negative, is connected with the binding screw, m, which communicates by the plate K with the commutator C, and with the battery.

To understand the effect of the condenser, it must be observed that at each break of the inducing current an extra current is produced in the same direction, which, continuing in a certain manner, prolongs its duration. It is this extra current which produces the spark that passes at each break between the hammer and the anvil; when the current is strong this spark rapidly alters the surfaces of the hammer and anvil, though they are of platinum. By interposing the condenser in the inducing circuit, the extra current, instead of producing so strong a spark, darts into the condenser; the positive electricity in the coating connected with i, and the negative in that connected with m. But the opposite electricities combining quickly by the thick wire of the primary coil, by the battery and the circuit CKm, give rise to a current contrary to that of the battery, which instantaneously demagnetises the bundle of soft iron; the induced current is thus shorter and more intense. The binding screws m and n on the base of the apparatus are for receiving this extra current.

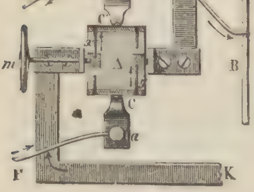


Fig. 686.

The *commutator* or *key* serves to break contact or send the current in either direction. The section in fig. 686 is entirely of brass, excepting the core A, which is ebonite; on the two sides are two brass plates CC′. Against these press two elastic brass springs, joined to

two binding screws, *a* and *c*, with which are also connected the electrodes of the battery. The current arriving at *a* ascends in C, thence by a screw *y* it attains the binding screw *b* and the bobbin; then returning by the plate K, which is connected with the hammer, the current goes to C′ by the screw *x*, descends to *c*, and rejoins the battery by the wire N. If by means of the milled head the key is turned 180 degrees, it is easy to see that exactly the opposite takes place; the current reaches the hammer by the plate K, and emerges at *b*. Finally, if it is only turned through 90 degrees, the elastic plates rest on the ebonite A, instead of on the plates CC′, and the current is broken.

The two wires fom the bobbin at *o* and *o′* (fig 684) are the two ends of the secondary wire. They are connected with the thicker wires PP′, so that the current can be sent in any desired direction. With large coils the hammer cannot be used, for the surfaces become so much heated as to melt. But M. Foucault has recently invented a mercury interrupter which is free from this inconvenience, and which is an important improvement.

817. **Effects produced by Ruhmkorff's coil.**—The high degree of tension which the electricity of induction coil machines possesses has long been known, and many luminous and calorific effects have been obtained by their means. But it is only since the improvements which Ruhmkorff has introduced into his coil, that it has been possible to utilise all the tension of induced currents, and to show that these currents possess the properties of statical as well as dynamical electricity.

Induced currents are produced in the coil at each opening and breaking of contact. But these currents are not equal either in duration or in tension. The direct current, or that on *opening*, is of shorter duration, but more tension; that of *closing* of longer duration but less tension. Hence if the two ends P and P′ of the fine wire (figs. 684 and 685) are connected, as there are two equal and contrary quantities of electricity in the wire the two currents neutralise each other. If a galvanometer is placed in the circuit, only a very feeble deflection is produced in the direction of the direct current. This is not the case if the two extremities P and P′ of the wire are separated. As the resistance of the air is then opposed to the passage of the currents, that which has most tension, that is, the direct one, passes in excess, and the more so the greater the distance of P and P′ up to a certain limit at which neither pass. There are then at P and P′ nothing but tensions alternately in contrary directions.

The effects of the coil, like those of the battery, may be classed under the heads *physiological*, *chemical*, *calorific*, *luminous*, *mechanical*; with this difference, that they are enormously more intense.

The *physiological* effects of Ruhmkorff's coil are very powerful; in fact, the shocks are so violent that many experimenters have been suddenly prostrated by them. A rabbit may be killed with two of Bunsen's elements, and a somewhat larger number of couples would kill a man.

The *calorific* effects are also easily observed; it is simply necessary to interpose a very fine iron wire between the two ends P and P′ of the

induced wire ; this iron wire is immediately melted, and burns with a bright light. A curious phenomenon may here be observed, namely, that when each of the wires P and P′ terminates in a very fine iron wire, and these two are brought near each other, the wire corresponding to the negative pole alone melts, indicating that the tension is greater at the negative than at the positive pole.

The *chemical* effects are very varied, inasmuch as the apparatus produces both dynamical electricity and electricity in a high state of tension. Thus, according to the shape and distance of the platinum electrodes immersed in water, and to the degree of acidulation of the water, either luminous effects may be produced in water without decomposition, or the water may be decomposed and the mixed gases disengaged at the two poles, or the decomposition may take place, and the mixed gases separate either at a single pole or at both poles.

Gases may also be decomposed or combined by the continued action of the spark from the coil. Becquerel and Frémy have found that if the current of a Ruhmkorff's coil be passed through a hermetically sealed tube containing air, as shown in fig. 687, nitrogen and oxygen combine to form nitrous acid.

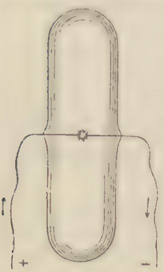


Fig. 687.

The *luminous* effects of Ruhmkorff's coil are also very remarkable, and vary according as they take place in air, in vapour, or in very rarefied vapours. In air the coil produces a very bright loud spark, which, with the largest-sized coils, has a length of 18 inches. In vacuo the effects are also remarkable. The experiment is made by connecting the two wires of the coil P and P′ with the two rods of the electrical egg (fig. 566) used for producing in vacuo the luminous effects of the electrical machine. A vacuum having been produced up to 1 or 2 millimeters, a beautiful luminous trail is produed from one knob to the other, which is virtually constant, and has the same intensity as that obtained with a powerful electrical machine when the plate is rapidly turned. This experiment is shown in fig. 693. Figure 691 represents a remarkable deviation which light undergoes when the hand is presented to the egg.

The positive pole of the current shows the greatest brilliancy ; its light is of a fiery red, while that of the negative pole is of a feeble violet colour ; moreover, the latter extends along all the length of the negative rod, which is not the case with the positive pole.

The coil also produces mechanical effects so powerful that with the largest apparatus glass plates two inches thick have been perforated. This result, however, is not obtained by a single charge, but by several successive charges.

The experiment is arranged as shown in fig. 688. The two poles of the induced current correspond to the binding screws *a* and *b* ; by means of a copper wire, the pole *a* is connected with the lower part of an apparatus for piercing glass like that already described (fig. 571), the

other pole is attached to the other conductor by a wire *d*. The latter is insulated in a large glass tube *r*, filled with shellac, which is run in while

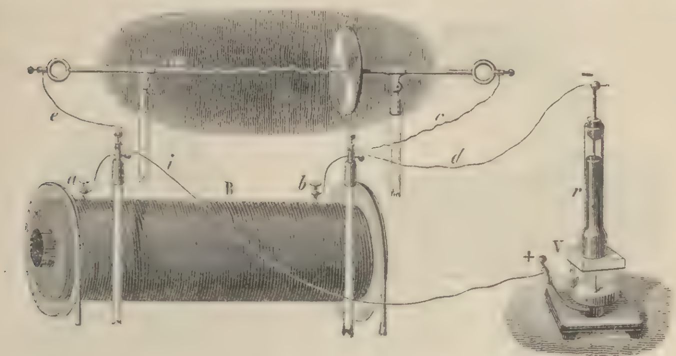


Fig. 688.

in a state of fusion. Between the two conductors is the glass to be perforated, V. When this presents too great a resistance, there is danger lest the spark pass in the coil itself, perforating the insulating layer which separates the wire, and then the coil is destroyed. To avoid this, two wires, *e* and *c*, connect the poles of the coil with two metallic rods whose distance from each other can be regulated. If then the spark cannot penetrate through the glass, it bursts across, and the coil is not injured.

The coil can also be used to charge Leyden jars. With a large coil giving sparks of 6 to 8 inches, and using 6 Bunsen's elements with a large surface, Ruhmkorff charged large batteries of 6 jars each, having about 3 square yards of coated surface.

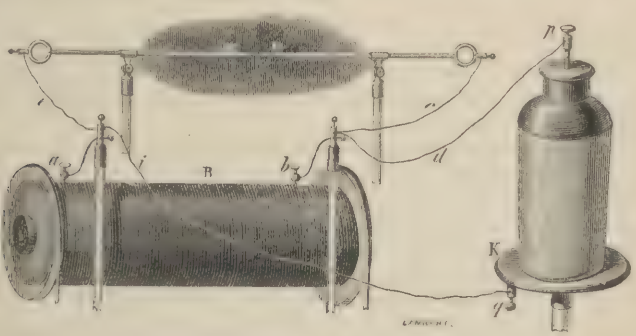


Fig. 689.

The experiment with a single Leyden jar (fig. 689) is made as follows. The armatures of the latter are in connection with the poles of the coil by

the wires *d* and *i*, and these same poles are also connected, by means of the wires *e* and *c*, with the two horizontal rods of a universal discharger

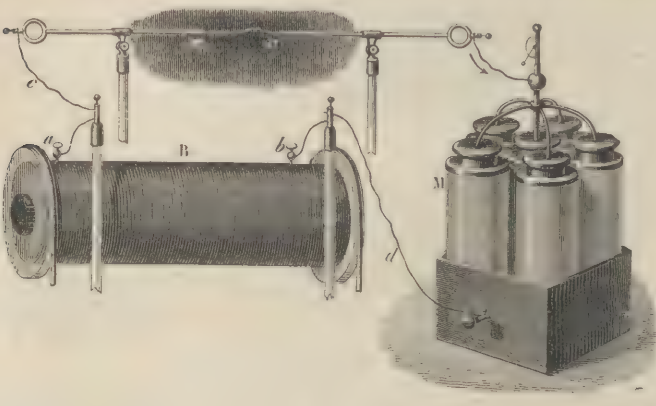


Fig. 690.

(fig. 560). The jar is then being constantly charged by the wires *i* and *d*, sometimes in one direction and sometimes in another, and as constantly discharged by the wires *e* and *c*; the discharge from *m* to *n* taking place as a spark two or three inches in length, very luminous, and producing a deafening sound; they are not the sparks of the electrical machine, but rather true lightning discharges.

To charge a battery the form of the experiment is somewhat varied; the external coating being connected with one pole of the coil by the wire *d*, and the internal coating with the other by the rods *m*, *n*, and the wire *c*. The rods *m* and *n* are not, however, in contact. If they were, as the two currents, the inverse and direct, pass equally, the battery would not be constantly charged and discharged; while from the distance between *m* and *n* the direct current, that of opening, which has higher tension, passes alone, and it is this which charges the battery.

818. **Stratification of the electric light.**—M. Quet has observed, in studying the electric light which Ruhmkorff's coil gives in a vacuum, that if some of the vapour of turpentine, wood spirit, alcohol, or bisulphide of carbon, etc., be introduced into the vessel before exhaustion, the aspect of the light is totally modified. It appears then like a series of alternately bright and dark zones, forming a pile of electric light between the two poles (fig. 692).

In this experiment it follows from the discontinuity of the current of induction, that the light is not continuous, but consists of a series of discharges which are nearer each other in proportion as the hammer *a* (fig. 685) oscillates more rapidiy. The zones appear to possess a rapid gyratory and undulatory motion. M. Quet considers this as an optical illusion;

for if the hammer is slowly moved by the hand, the zones appear very distinct and fixed.

The light of the positive pole is most frequently red, and that of the

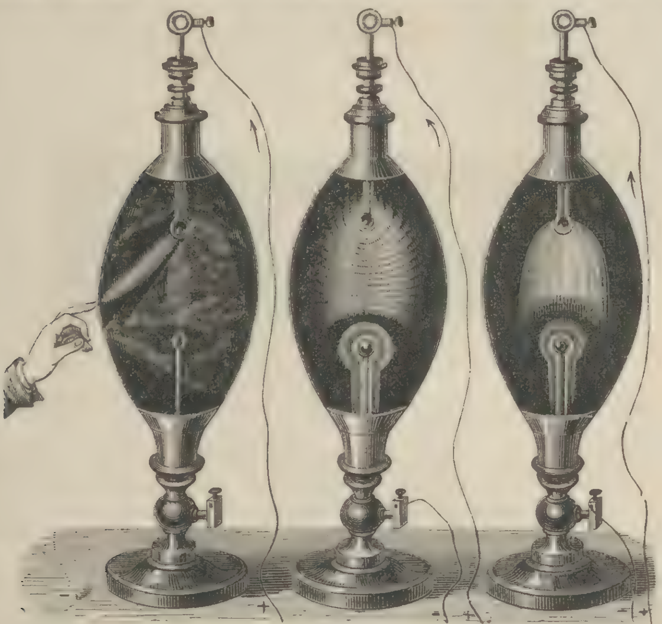


Fig. 691. Fig. 692. Fig. 693.

negative pole violet. The tint varies, however, with the vapour or gas in the globe.

M. Despretz has observed that the phenomena obtained by Ruhmkorff and by Quet, with a discontinuous current, are also reproduced with an ordinary continuous current, with this important difference, that the continuous current requires a considerable number of couples, while the discontinuous current of the coil only requires a single element. It is remarkable that the luminous effects of this coil are very little increased by an increase in the number of elements.

819. **Geissler's tubes.**—The brilliancy and beauty of the stratification of the electric light are most remarkable when the discharge of the Ruhmkorff's coil takes place in glass tubes containing a highly rarefied vapour or gas. These phenomena, which have been investigated by Masson, Grove, Gassiot, Plücker, etc., are produced by means of sealed glass tubes constructed by Geissler, of Bonn. These tubes are filled with different gases or vapours, and are then exhausted, so that the pressure does not exceed half a millimeter. At the ends of the tubes two platinum wires are soldered into the glass.

When the two platinum wires are connected with the ends of a Ruhmkorff's coil, magnificent lustrous striæ, separated by dark bands, are produced all through the tube. These striæ vary in shape, colour, and lustre with the degree of the vacuum, the nature of the gas or vapour, and the dimensions of the tube. The phenomenon has occasionally a still more brilliant aspect from the fluorescence which the electric discharge excites in the glass.

Fig. 694 represents the striæ given by hydrogen under half a milli-

Fig. 694.

meter of pressure ; in the bulbs the light is white, in the capillary parts it is red.

Fig. 695 shows the striæ in carbonic acid under a quarter of a millimeter pressure ; the colour is greenish, and the striæ have not the same form as in hydrogen. In nitrogen the light is orange yellow.

Plücker has found that the light in Geissler's tubes does not depend

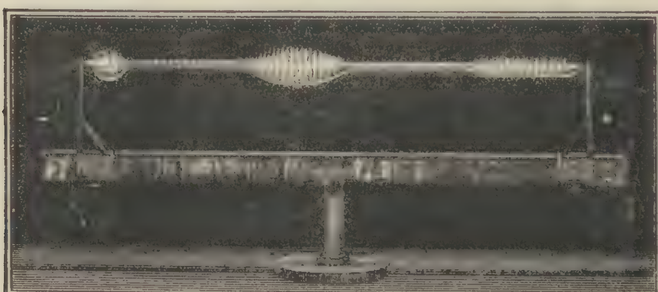


Fig. 695.

on the substance of the electrodes, but simply on the nature of the gas or vapour in the tube. He has found that the lights furnished by hydrogen, nitrogen, carbonic oxide, etc., give different spectra when they are decomposed by a prism. The discharge of the coil which passes through a highly rarefied gas would not pass through a perfect vacuum, and the presence of a ponderable substance is absolutely necessary for the passage of electricity.

By the aid of a powerful magnet Plücker tried the action of mag-

netism on the electric discharge in a Geissler's tube, as Davy had done with the ordinary voltaic arc, and obtained many curious results, one of which may be mentioned. He found that where the discharge is perpendicular to the line of the poles, it is separated into two distinct parts, which can be referred to the different action exerted by the electromagnet on the two extra currents produced in the discharge.

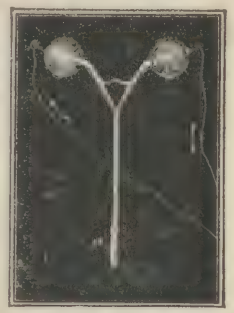


Fig. 696.

The light of Geissler's tubes has been recently applied to medical purposes. A long capillary tube is soldered to two bulbs provided with platinum wires; this tube is bent in the middle, so that the two branches touch, and their extremities are twisted, as shown at *a* in fig. 696. This tube contains a highly rarefied gas, like those previously described, and, when the discharge passes, a light is produced at *a*, bright enough to illuminate any cavity of the body into which the tube is introduced.

820. **Rotation of induced currents by magnets.**—De la Rive has recently devised an experiment which shows in a most ingenious manner that magnets act on the light in Geissler's tubes in accordance with the laws with which they act on any other moveable conductor.

This apparatus consists of a glass globe or electrical egg, provided at one end with two stopcocks, one of which can be screwed on the air pump, and the other, which is a stopcock like that of Gay Lussac (347), serves to introduce a few drops of liquid into the globe. At the other end a tubulure is cemented, through which passes a rod of soft iron about $\frac{4}{5}$ of an inch in diameter, the top of which is about the centre of the globe. Except at the two ends, this bar is entirely covered with a very thick insulating layer of shellac, then with a glass tube also coated with shellac, and finally with another glass tube uniformly coated with a layer of wax. This insulating layer must be at least $\frac{2}{5}$ of an inch thick. Inside the globe the insulating layer is surrounded at *x* with a copper ring connected by means of a copper wire with a binding screw, *c*.

The vessel having been exhausted as completely as possible, a few drops of ether or of turpentine are introduced by means of the stopcock *a*; it is again exhausted, so that the vapour remaining is highly rarefied.

A thick disc of soft iron, *o*, provided with a binding screw, is then placed on one of the branches of a powerful electromagnet, and the end *m* of the rod *mn* is placed on this disc, while at the same time one of the ends of the secondary wire of Ruhmkorff's coil is connected with the binding screw *c*, and the other with the knob *o*. If then the coil is worked without setting in action the electromagnet, the electricity of the wire *s* passes to the top *n* of the soft iron rod, and that of the second wire to the ring *x*, and a more or less irregular luminous sheaf appears

on the inside of the globe round the rod as in the experiment of the electric egg.

But if a voltaic current passes into the electromagnet the phenomenon

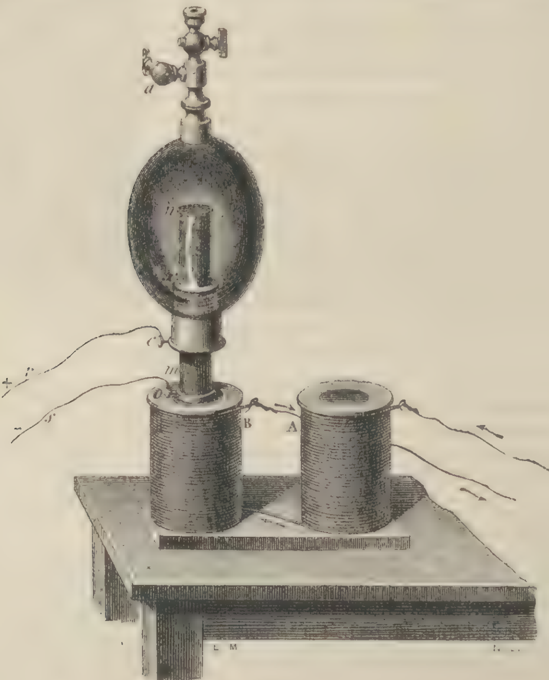


Fig. 697.

is different ; instead of starting from different points of the upper surface *n*, and the ring *x*. the light is condensed and emits a single luminous arc from *n* to *x*. Further, and this is the most remarkable part of the experiment, this arc turns slowly round the magnetised cylinder *mn*, sometimes in one direction, and sometimes in another, according to the direction of the induced current, or the direction of the magnetism. As soon as the magnetism ceases the luminous phenomenon reverts to its original appearance.

This experiment is remarkable as having been devised *à priori* by De la Rive to explain, by the influence of terrestrial magnetism, a kind of rotatory motion from east to west, observed in the aurora borealis. The rotation of the luminous arc in the above experiment can evidently be referred to the rotation of currents by magnets.

Geissler has constructed a very useful form of the above experiment, in which the globe is exhausted once for all. Apart from the purpose for which it was originally devised it is a very convenient arrangement for demonstrating the action of magnets on currents.

821. **Heat developed by the induction of powerful magnets on bodies in motion.**—We have already seen in Arago's experiments (802) that a rotating copper disc acts at a distance on a magnetic needle, communicating to it a rotatory motion. We shall presently see that a cube of copper, rotating with great velocity, is suddenly stopped by the influence of the poles of two strong magnets (823). It is clear that in order to prevent the rotation of the needle or of the copper, a certain mechanical force must be consumed in overcoming the resistance which arises from the inductive action of the magnet. Reasoning upon the theory of the transformation of mechanical work into heat, which has occupied physicists in the last few years (451), it has been attempted to ascertain what quantity of heat is developed by the action of induced currents under the influence of powerful magnets. Joule, with a view of determining the mechanical equivalent of heat, coiled a quantity of copper wire round a cylinder of soft iron, and having enclosed the whole in a glass tube full of water, he imparted to the system a rapid rotation between the branches of an electromagnet. A thermometer placed in the liquid served to measure the quantity of heat produced by the induced currents in the soft iron and the wire round it. It was thus found that the heat developed was proportional to the square of the magnetism evoked, and was equivalent to the work used in the rotation.

Foucault has recently made a remarkable experiment by means of the apparatus represented in fig. 698. It consists of a powerful electromagnet

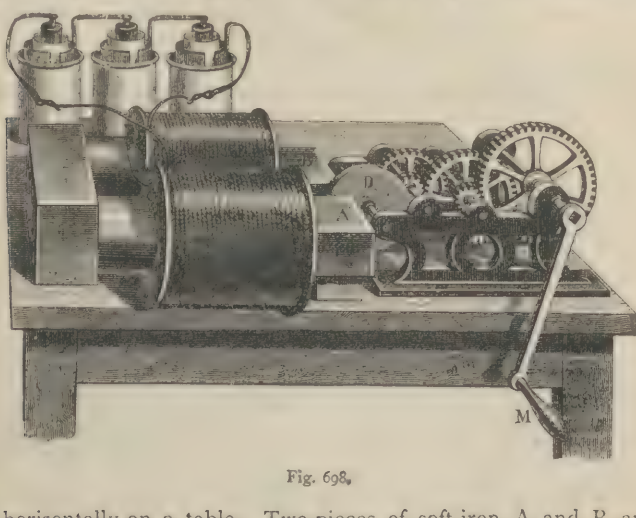


Fig. 698.

fixed horizontally on a table. Two pieces of soft iron, A and B, are in contact with the poles of the magnet, and becoming magnetic by induction, they concentrate their magnetic inductive action on the two faces of a metallic disc, D; this disc, which is of copper, is 3 inches in diameter, and a quarter of an inch thick, partly projects between the pieces A and

B, and can be moved by means of a handle and a series of toothed wheels with a velocity of 150 to 200 turns in a second.

So long as the current does not pass through the wire of the electromagnet, very little resistance is experienced in turning the handle, and when once it has begun to rotate rapidly, and is left to itself, the rotation continues in virtue of the acquired velocity. But if the current passes, the disc and other pieces stop almost instantaneously; and if the handle is turned considerable resistance is felt. If, spite of this, the rotation be continued, the force used is transformed into heat, and the disc becomes heated to a remarkable extent. In an experiment made by M. Foucault the temperature of the disc rose from 10° to 61°, the current being formed by three of Bunsen's elements; with six the resistance was such that the rotation could not long be continued.

CHAPTER VII.

OPTICAL EFFECTS OF POWERFUL MAGNETS. DIAMAGNETISM.

822. **Optical effects of powerful magnets.**—Faraday observed in 1845, that a powerful electromagnet exercises an action on many substances, such that if a polarised ray traverses them in the direction of the line of the magnetic poles, the plain of polarisation is deviated either to the right or to the left, according to the direction of the magnetism.

Figure 699 represents Faraday's apparatus, as constructed by Ruhmkorff. It consists of two very powerful electromagnets, M and N, fixed

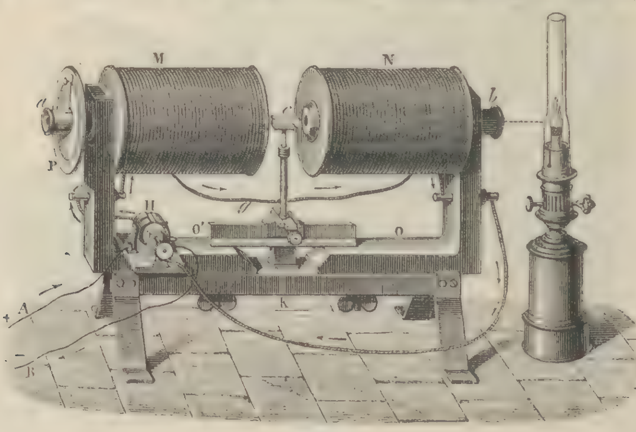


Fig. 699.

on two iron supports, OO′, which can be moved on a support, K. The current from a battery of 10 or 11 Bunsen's elements passes by the wire

A to the commutator H, the bobbin M, and then to the bobbin N, by the wire *g*, descends in the wire *i*, passes again to the commutator, and emerges at B. The two cylinders of soft iron, which are in the axis of the bobbins, are perforated by cylindrical holes, to allow the luminous rays to pass. At *b* and *a* there are two Nicol's prisms, the first serving as polariser, and the second as analyser. By means of a limb this latter is turned round the centre of a graduated circle, P.

The two prisms being then placed so that their principal sections are perpendicular to each other, the prism *a* completely extinguishes the light transmitted through the prism *b*. If at *c*, on the axis of the two coils, a plate be placed with parallel faces, either of ordinary or flint glass, light is still extinguished so long as the current does not pass; but when the communications are established, the light reappears. It is now coloured, and if the analyser be turned from left or right, according to the direction of the current, the light passes through the different tints of the spectrum, as is the case with plates of quartz cut perpendicularly to the axis (609). Becquerel has shown that a large number of substances can also rotate the plane of polarisation under the influence of powerful magnets. Faraday assumes that in these experiments the rotation of the plane of polarisation is due to an action of the magnets on the luminous rays, while Biot and Becquerel ascribe the phenomena to a molecular action of the magnet on the transparent bodies submitted to its influence.

823. **Diamagnetism.**—Coulomb observed, in 1802, that magnets act upon all bodies in a more or less marked degree; this action was at first attributed to the presence of ferruginous particles. Brugmann also found that certain bodies, for instance, bars of bismuth, when suspended between the poles of a powerful magnet, do not set *axially* between the poles, that is, in the line joining the poles, but *equatorially*, or at right angles to that line. This phenomenon was explained by the assumption that the bodies were transversely magnetic. Faraday made the important discovery in 1845 that all solids and liquids are either attracted or repelled by a powerful electromagnet. The bodies which are attracted

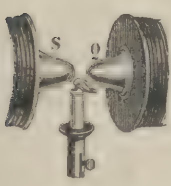


Fig. 700.

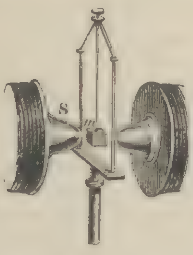


Fig. 701.

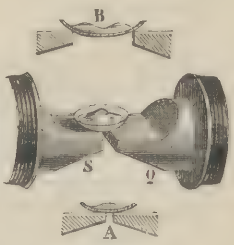


Fig. 702.

are called magnetic or *paramagnetic* substances, and those which are repelled are *diamagnetic* bodies. Among the metals, iron, nickel, cobalt,

manganese, platinum, cerium, osmium, and palladium are magnetic; while bismuth, antimony, zinc, tin, mercury, lead, silver, copper, gold, and arsenic are diamagnetic, bismuth being the most so and arsenic the least. The diamagnetic effects can only be produced by means of very powerful magnets, and it is by means of Faraday's apparatus that they have been discovered and studied. In experimenting on the diamagnetic effects—solids, liquids, and gases—armatures of soft iron, S and Q, (figs. 700-702) of different shapes are screwed on the magnets.

i. *Diamagnetism of solids.* If a small cube of copper, suspended by a fine silk thread between the poles of the magnet (fig. 701), be in rapid rotation between the poles of an electromagnet, it stops the moment the current passes through the bobbins. If the moveable piece have the form of a small rectangular bar it sets *equatorially*, or at right angles to the axis of the bobbins, if it is a diamagnetic substance, such as bismuth, antimony, or copper; but *axially*, or in the direction of the axis, if it is a magnetic substance, such as iron, nickel, or cobalt.

Besides the substances enumerated above, the following are diamagnetic: rock crystal, alum, glass, phosphorus, sulphur, sugar, bread; and the following are magnetic: many kinds of paper and sealing-wax, fluorspar, graphite, charcoal, etc.

ii. *Diamagnetism of liquids.* Liquids also present the phenomena of magnetism and of diamagnetism. In making the experiment, very thin glass tubes filled with the substance are suspended between the poles instead of the cube *m* in the figure 701. If the liquids are magnetic, such as solutions of iron or cobalt, the tubes set axially; if diamagnetic, like water, alcohol, ether, essence of turpentine, and most saline solutions, the tubes set equatorially.

Very remarkable changes take place in the direction of magnetic and diamagnetic substances when they are suspended in liquids. A magnetic substance is indifferent in an equally strong magnetic liquid; it sets equatorially in a stronger magnetic substance, and axially in a substance which is less strongly magnetic; it sets axially in all diamagnetic liquids.

A diamagnetic substance surrounded by a magnetic or diamagnetic substance sets equatorially. According to its composition, glass is sometimes magnetic and sometimes diamagnetic, and as in these investigations glass tubes are used for containing the liquids, its deportment must first be determined, and then taken into account in the experiment.

The action of powerful magnets on liquids may also be observed in the following experiment devised by Plücker. A solution of a magnetic liquid is placed on a watch glass between the two poles, S and Q, of a powerful electromagnet. When the current passes, the solution forms the enlargement represented in fig. 702; this continues as long as the current passes, and is produced to different extents with all magnetic liquids. The changes in the aspects of the liquids are, however, so small as to require careful scrutiny to detect their existence. A method of magnifying these changes so as to render them visible to large audiences, has recently been devised by Mr. Barrett. A source of light is placed above the watch glass containing a drop of the solution to be tried. Below the watch glass, and

between the legs of the magnet, is placed a mirror at an angle of 45°. By this means the beam of light passing through the watch glass is reflected at right angles on to a screen, where an image of the drop is focussed by a lens. If now a drop of a diamagnetic liquid, such as water, or better sulphuric acid, be placed on the watch glass, as soon as the current passes, the flattened drop retreats from the two poles, and gathers itself up into a little heap, as at A (fig. 702). So doing it forms a double convex lens, by which the light is brought to a short focus below the drop, an effect instantly seen on the screen. When the current is interrupted the drop falls, and the light returns to its former appearance. A magnetic liquid, such as a solution of perchloride of iron, has exactly the opposite effect. The drop attracted to the two poles becomes flattened, and instead of a plano-convex shape, at which it rests, it becomes nearly concavo-convex as at B. The light is dispersed, and the effect manifest on the screen. Instead of a mirror and lens, a sheet of white paper may be placed in an inclined position under the watch glass, and the effects are somewhat varied, but equally well pronounced.

iii. *Diamagnetism of gases.* Bancalari observed that the flame of a candle placed between the two poles in Faraday's apparatus was strongly repelled (fig. 700). All flames present the same phenomenon to different extents, resinous flames or smoke being most powerfully affected.

The magnetic deportment of gases may be exhibited for lecture purposes by inflating soap bubbles with them between the poles of the electromagnet, and projecting on them either the lime or the electric light.

Faraday has experimented on the magnetic or diamagnetic nature of gases. He allowed gas mixed with a small quantity of a visible gas or vapour, so as to render it perceptible, to ascend between the two poles of a magnet, and observed their deflections from the vertical line in the axial or equatorial direction; in this way he found that oxygen was least, nitrogen more, and hydrogen most diamagnetic. With iodine vapour, produced by placing a little iodine on a hot plate between the two poles, the repulsion is strongly marked. Becquerel, who has made important researches on magnetism, has found that oxygen is most strongly magnetic of all gases, and that a cubic yard of this gas condensed would act on a magnetic needle like 5·5 grains of iron. Faraday has found that oxygen, although magnetic under ordinary circumstances, becomes diamagnetic when the temperature is much raised, and that the magnetism or diamagnetism of a substance depends on the medium in which it is placed. A substance, for instance, which is magnetic in vacuo, may become diamagnetic in air.

In the crystallised bodies which do not belong to the regular system, the directions in which the magnetism or diamagnetism of a body is most easily excited, are generally related to the crystallographic axis of the substance. The optic axis of the uniaxial crystals sets either axially or equatorially when a crystal is suspended between the poles of an electromagnet. Faraday has assumed from this the existence of a magnetocrystalline force, but it appears probable from Knoblauch's researches,

that the action arises from an unequal density in different directions, inasmuch as unequal pressure in different directions produces the same result.

According to Plücker for a given unit of magnetising force, the specific magnetisms developed in equal weights of the undermentioned substances are represented by the following numbers, those bodies with the minus sign prefixed being diamagnetic:

Iron	1,000,000	Nickel oxide	287
Cobalt	1,009,000	Water	−25
Nickel	465,800	Bismuth	−23·6
Iron oxide	759	Phosphorus	−13·1

iv. *Detonation produced by the rupture of a current under the influence of a powerful electromagnet.* The following experiment devised by Ruhmkorff is a remarkable effect of Faraday's apparatus. When the two ends of a stout wire in which the current of the electromagnet passes, are placed between the two poles, S and Q, of figure 700, that is to say, when the current is closed between S and Q, this closing takes place without a spark and without noise, or merely a feeble noise and a spark. But when the two ends are separated, and the current is hence broken, a violent noise is heard almost as strong as the report of a pistol. It would appear to be the extra current, the intensity of which is greatly increased by the influence of the two poles.

CHAPTER VIII.

THERMO-ELECTRIC CURRENTS.

824. **Thermo-electricity.**—In 1821, Professor Seebeck, in Berlin, found that by heating one of the junctions of a metallic circuit, consisting of two metals soldered together, an electric current was produced. This phenomenon may be shown by means of the apparatus represented in fig. 703, which consists of a plate of copper, *mn*, the ends of which are bent and soldered to a plate of bismuth, *op*. In the interior of the circuit is a magnetic needle moving on a pivot. When the apparatus is placed in the magnetic meridian, and one of the solderings gently heated, as shown in the figure, the needle is deflected in a manner which indicates the passage of a current from *n* to *m*, that is, from the heated to the cool junction in the copper. If, instead of heating the junction *n*, it is cooled by ice or by placing upon it cotton wool moistened with ether, the other junction remaining at the ordinary temperature, a current is produced, but in the opposite direction; that is to say, from *m* to *n*. In both cases the current is more energetic in proportion as the *difference* in temperature of the solderings is greater.

Seebeck gives the name *thermo-electric* to this current, and the couple

which produces it, to distinguish it from the *hydro-electric* or ordinary voltaic current and couple.

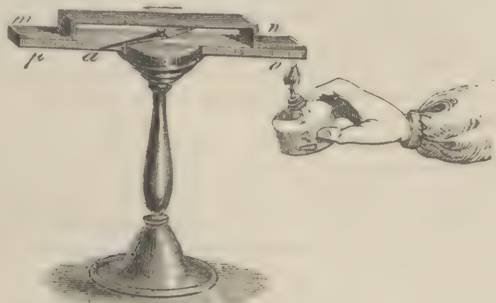


Fig. 703.

825. **Thermo-electric series.**—If small bars of two different metals are soldered together at one end while the free ends are connected with the wires of a galvanometer, and if now the point of junction of the two metals be heated, a current is produced, the direction of which is indicated by the deflection of the needle of the galvanometer. Moreover the intensity of the current calculated from the deflection of the galvanometer is proportional to the electromotive force of the *thermo-element.* By experimenting in this way with different metals, they may be formed in a list such that each metal gives rise to positive electricity when associated with one of the following, and negative electricity with one of those that precede; that is, that in heating the soldering, the positive current goes from the positive to the negative metal across the soldering, just as if the soldering represented the liquid in a hydro-electrical element; hence out of the element, in the connecting wire in the galvanometer for instance, the current goes from the negative to the positive metal.

Thus a couple, bismuth-antimony, heated at the junction would correspond to a couple, zinc-copper, immersed in sulphuric acid. The following is a list drawn up from Dr. Matthiessen's researches, which also gives comparative numerical values for the electromotive force.

Bismuth	+25	Gas coke	−0·1
Cobalt	9	Zinc	0·2
Potassium	5·5	Cadmium	0·3
Nickel	5	Strontium	2·0
Sodium	3	Arsenic	3·8
Lead	1·03	Iron	5·2
Tin	1	Red phosphorus	9·6
Copper	1	Antimony	9·8
Platinum	0·7	Tellurium	179·9
Silver	1·0	Selenium	−290·0

The meaning of the numbers in this list is that, taking the electromo-

tive force of the copper-silver couple as unity, the electromotive force of any pair of metals is expressed by the difference of the numbers where the signs are the same and by the sum where the signs are different. Thus the electromotive force of a bismuth-nickel couple would be $25-5=20$; of a cobalt-iron $9-(-5{\cdot}2)=14{\cdot}2$, and of an iron-antimony $-5{\cdot}2-9{\cdot}8=-4{\cdot}6$. Where the positive sign is fixed, the current is from the other metal to silver across the soldering; and where the negative, from silver to that metal.

Hence of these bodies, bismuth and selenium produce the greatest electromotive force; but from the expense of this latter element, and on account of its low conducting power, antimony is generally substituted. The antimony is the negative metal but the positive pole, and the bismuth the positive metal but the negative pole, and the current goes from bismuth to antimony across the junction.

If copper wires connected with the ends of a galvanometer are soldered together to the ends of an antimony rod, and if one of the junctions is heated to 50°, the other being maintained at 0°, a certain deflection is observed in the galvanometer. If similarly a compound bar, consisting of antimony and tin soldered together, be connected with the ends of the galvanometer, and if the junction copper-tin, and the junction tin-antimony, be heated to 50°, while the junction antimony-copper is kept at 0°, the deflection is the same as in the previous case. Hence the electromotive force produced by heating the two junctions, copper-tin and tin-antimony, is equal to the electromotive force produced by heating the copper-antimony.

Becquerel found with a number of couples where one end of the junction was heated to a given temperature and the other kept at 0°, that the intensity of the current was proportional to the temperature at the junction. If the two junctions are at any given temperature, the intensity of the current is proportional to the difference of the temperature of the two places, provided that this does not exceed 50°.

The direction of the current frequently changes when the temperature of the couple is raised beyond a certain limit. Thus, in a copper and iron circuit the current goes from copper to iron through the heated part, provided the temperature does not exceed 300°; at a higher temperature the current changes its direction, and goes from iron to copper.

As compared with ordinary hydro-electric currents the electromotive force of thermocurrents is very small; thus the electromotive force of a bismuth-copper element with a difference of 100° C. in the temperatures of their junctions is according to Wheatstone $\frac{1}{97}$, and according to Neumann $\frac{1}{256}$ that of Daniell's element: the electromotive force of an iron-argentan couple with 10 to 15° difference of temperatures in their junctions is $\frac{1}{6600}$ that of a Daniell's according to Kohlrausch.

826. **Causes of thermo-electric currents.**—The thermo-electric currents cannot be attributed to contact, for they can be produced in circuits formed of a single metal. Nor do they arise from chemical actions, for Becquerel has found that they are formed in hydrogen, and even in vacuo. The same physicist ascribes them to the unequal propagation of

heat in the different parts of the circuit. He found that when all the parts of a circuit are homogeneous, no current is produced on heating, because the heat is equally propagated in all directions. This is the case if the wires of the galvanometer are connected by a second copper wire. But if the uniformity of this is destroyed by coiling it in a spiral, or by knotting it, the needle indicates by its deflection a current going from the heated part to that in which the homogeneity has been destroyed. If the ends of the galvanometer wires be coiled in spiral, and one end is heated and touched with the other, the current goes from the heated to the cooled end.

When two plates of the same metal, but at different temperatures, are placed in a fused salt such as borax, which conducts electricity but exerts no chemical action, a current passes from the hotter metal through the fused salt to the colder one. Hot and cold water in contact produce a current which goes from the warm water to the cold.

Svanberg has found that the thermo-electromotive force is influenced by the crystallisation; for instance, if the cleavage of bismuth is parallel to the face of contact, it is greater than if both are at right angles, and that the reverse is the case with antimony. Thermo-electric elements may be constructed of either two pieces of bismuth or two pieces of antimony, if in the one the principal cleavage is parallel to the place of contact, and in the other is at right angles. Hence the position of metals in the thermo-electric series is influenced by their crystalline structure.

827. **Thermo-electric couples.**—From what has been said it will be understood that a thermo-electric couple consists of two metals soldered together, the two ends of which can be joined by a conductor. Fig. 704 represents a bismuth-copper couple; fig. 705 represents a series of couples used by M. Pouillet. It consists of a bar of bismuth bent twice at right angles, at the ends of which are soldered two copper strips, *c*, *d*, which terminate in two binding screws fixed on some insulating material.

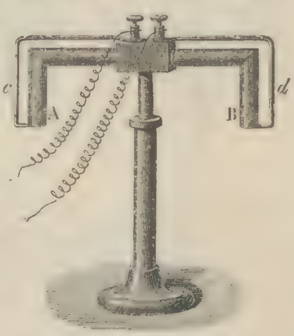


Fig. 704.

When several of these couples are joined so that the second copper of the first is soldered to the bismuth of the second, then the second copper of this to the bismuth of the third, and so on, this arrangement constitutes a thermo-electric battery, which is worked by keeping the odd solderings, for instance, in ice, and the even ones in water, which is kept at 100°.

828. **Nobili's thermo-electric pile.**—Nobili devised a form of thermo-electric battery, or pile as it is usually termed, in which there are a large number of elements in a very small space. For this purpose he joined the couples of bismuth and antimony in such a manner, that after having formed a series of five couples, as represented in fig. 707, the bismuth from *b* was soldered to the antimony of a second series arranged similarly;

the last bismuth of this to the antimony of a third, and so on for four vertical series, containing together 20 couples, commencing by antimony,

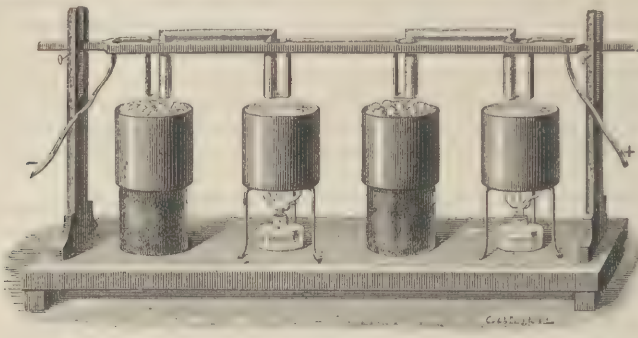


Fig. 705.

finishing by bismuth. Thus arranged, the couples are insulated from one another by means of small paper bands covered with varnish, and then enclosed in a copper frame, P (fig. 706), so that only the solderings appear at the two ends of the pile. Two small copper binding-screws, *m* and *n*, insulated in an ivory ring, communicate in the interior, one with the first antimony, representing the positive pole, and the other with the last bismuth, representing the negative pole. These binding screws communicate with the extremities of a galvanometer wire when the thermo-electric current is to be observed.

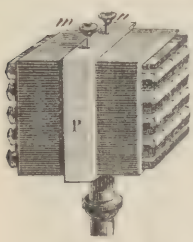


Fig. 706.

Fig. 707.

829. **Becquerel's thermo-electric battery.**—Becquerel has found that artificial sulphuret of copper heated from 200° to 300° is powerfully positive, and that a couple of this substance and copper has an electromotive force nearly ten times as great as that of the bismuth and copper couple in fig. 704. Native sulphuret, on the contrary, is powerfully negative. As the artificial sulphuret only melts at about 1035°, it may be used at very high temperatures. The metal joined with it is German silver (90 of copper and 10 of nickel). Fig. 708 represents the arrangement of a battery of 50 couples arranged in two series of 25. Fig. 710 gives on a larger scale the view of a single couple, and fig. 709 that of 6 couples in two series of 3. The sulphuret is cut in the form of rectangular prisms, 10 centimeters in length, by 18mm. in breadth, and 12mm. thick. In front is a plate of German silver *m*, intended to protect the sulphuret from roasting when it is placed in a gas flame. Below there is a plate of German silver MM, which is bent several times so as to be joined to the

sulphuret of the next, and so on. The couples, thus arranged in two series of 25, are fixed to a wooden frame supported by two brass columns

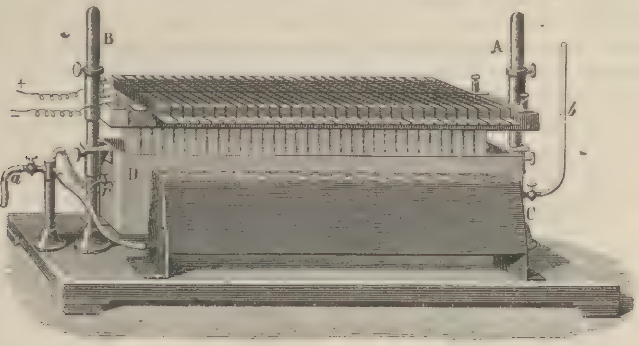


Fig. 708.

A B, on which it can be more or less raised. Below the couples there is a brass trough, through which water is constantly flowing; arriving by the tube *b* and emerging by the stopcock *r*. The plates of German silver are thus kept at a constant temperature. On each side of the trough are two long burners on the Argand principle fed by gas from a caoutchouc tube *a*. The frame being sufficiently lowered, the ends are kept at a temperature of 200° to 300°. For collecting the current, two binding screws are placed on the left of the frame, one communicating with the first sulphuret, that is, the positive pole, and the other with the last

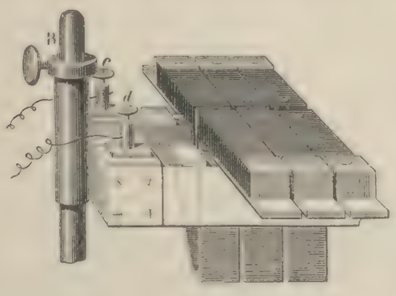


Fig. 709.

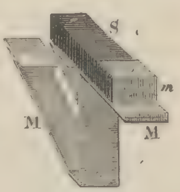


Fig. 710.

German silver, or the negative pole. At the other end of the frame are two binding screws, which facilitate the arrangement of the couples in different ways.

The resistance of sulphuret of copper is great, and consequently the current can acquire great tension. It may be used for telegraphing at a great distance, and passed into an electromagnet can lift a weight of 200 pounds. It can raise a short piece of fine iron wire to redness, and freely

decomposes water. The electromotive force of a Daniell's cell is equal to about 8 or 9 of these couples.

830. **Melloni's thermomultiplier.**—We have already noticed the use which Melloni has made of Nobili's pile, in conjunction with the galvanometer, for measuring the most feeble alterations of temperature. The arrangenent he used for his experiment is represented in fig. 711.

On a wooden base, provided with levelling screws,. a graduated copper rule, about a yard long, is fixed edgeways. On this rule the various parts

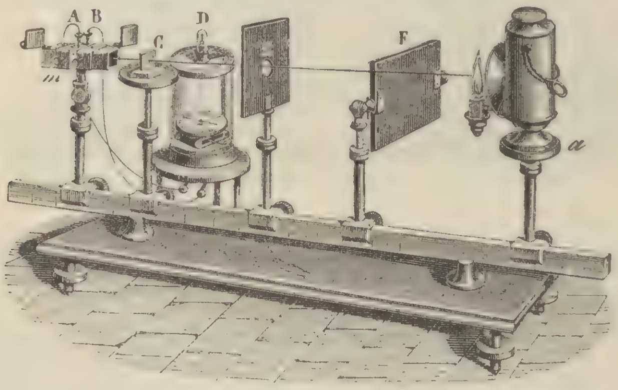


Fig. 711.

composing the apparatus are placed, and their distances can be fixed by means of binding screws. *a* is a support for a Locatelli's lamp, or other source of heat; F and E are screens; C is a support for the bodies experimented, and *m* is a thermo-electrical battery. Near the apparatus is a galvanometer, D; this has only a comparatively few turns of a tolerably thick (1 mm.) copper wire; for the electromotive force of the thermocurrents is small, and as the internal resistance is small too, for it only consists of metal, it is clear that no great resistance can be introduced into the circuit if the current is not to be completely stopped. Such galvanometers are called *thermomultipliers*. The delicacy of this apparatus is so great that the heat of the hand is enough at a distance of a yard from the pile to deflect the needle of the galvanometer.

In using it for measuring temperature, the relation of the deflection of the needle, and therefore of the intensity of the current, to the difference of the temperatures of the two ends, must be determined. That known, the temperature of the ends not exposed to the source of heat being known, the observed deflection gives the temperature of the other, and therewith the intensity of the source of heat.

831. **Properties and uses of thermo-electric currents.**—Thermoelectric currents are of extremely low tension, but of great constancy; for their opposite junctions, by means of melting ice and boiling water, can easily be kept at 0° and 100° C. On this account, Ohm used them in the

experimental establishment of his law. They can produce all the actions of the ordinary battery in kind, though in less degree. By means of a thermo-electrical pile consisting of 769 elements of iron and German silver, the ends of which differed in temperature by about 10° to 15°, Kohlrausch proved the presence of free positive and negative electricity at the two ends of the open pile respectively. He found that the density of the free electricity was nearly proportional to the number of elements, and also that the electromotive force of a single element under the above circumstances was about $\frac{1}{6600}$ that of a single Daniell's element. On account of their feeble tension, thermo-electric piles produce only feeble chemical actions. Botto, however, with 120 platinum and iron wires, has decomposed water.

Besides these, sparks can be obtained on breaking circuit, and magnetic and physiological effects produced as with other sources of electricity.

832. **Becquerel's electrical thermometer.**—This consists of a copper and iron wire of many yards in length soldered at their ends, but otherwise insulated from each other by being covered with gutta-percha. The copper wire is cut twice and connected with the binding screws of a galvanometer (fig. 712). One of the solderings is arranged in the place

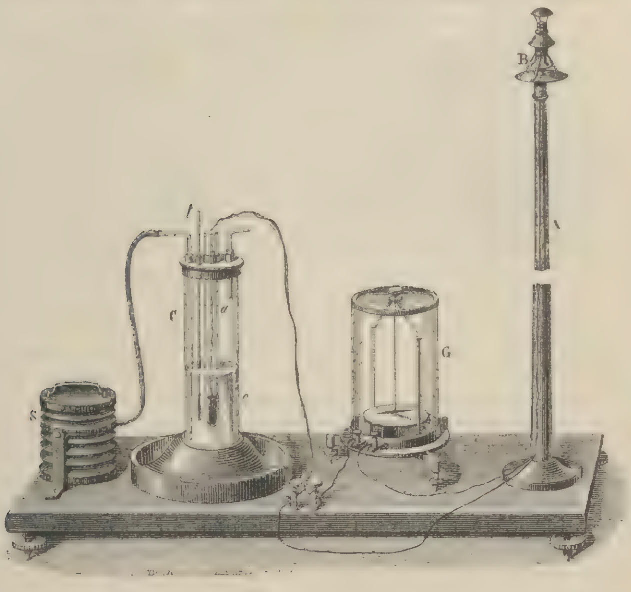


Fig. 712.

whose temperature is to be measured. In the figure it is at B at the top of a mast A, and is underneath a hood, which protects it from rain and the sun, but allows air to circulate round it.

The other soldering is immersed in mercury contained in a glass tube, and which in turn is placed in a larger cylinder C containing ether. On one side is a very delicate thermometer *t*, which indicates the temperature of the ether. By means of a small bellows S, a caoutchouc tube and a glass tube, a current of air can be sent through the ether, which being thus vaporised is cooled. If, on the contrary, the temperature of the ether is to be raised, a tinplate vessel containing hot water is brought near the cylinder C.

These details being known, when the solderings are at the same temperature no current is produced in the circuit, and the galvanometer remains at zero; but when there is the least difference in temperature, the deflection of the galvanometer tells which of these solderings is the hottest. If it is the one which is immersed in the mercury, the bellows is worked until the ether being cooled the galvanometer reverts to zero. The two solderings being then at the same temperature, the thermometer *t* at once indicates the temperature in B.

Becquerel has applied this instrument to investigations on the temperature of the ground at various depths, that of the air at different heights, and also on the temperature of plants and animals.

833. **Becquerel's electric pyrometer.**—This apparatus is an improved form of one originally devised by Pouillet. It consists (fig. 713) of two wires one of platinum and the other of palladium, both two meters in length and a square millimeter in section. They are not soldered at the ends but firmly tied for a distance of a centimeter with fine platinum wire. The palladium wire is enclosed in a thin porcelain tube; the platinum wire is on the outside, and the whole is enclosed in a larger porcelain tube P. At the end of this is the junction which is adjusted in the place the temperature of which is to be investigated. At the other end project the platinum and palladium wires *m* and *n*, which are soldered to two copper wires that lead the current to a magnetometer G. These series at the junction are placed in glass tubes immersed in ice, so that, being both at the same temperature, they give rise to no current.

The magnetometer which was devised by Weber is nothing more than a large galvanometer. It consists of a magnetised bar placed in the centre of a copper frame which deadens the oscillations (802) and rests on a stirrup, which in turn is suspended to a long and very fine platinum wire. On the stirrup is fixed a mirror M, which moves with the magnet, and gives by reflection the image of divisions traced on a horizontal scale E at a distance. These divisions are observed by a telescope. With this view, before the current passes, the image of the zero of the scale is brought to the micrometer wire of the telescope; then the slightest deflection of the mirror gives the image of another division, and therefore the angular deflection of the bar. This angle is always small and should not exceed 3 or 4 degrees: this is effected by placing, if necessary, a rheostate in the circuit, or any resistance coil. The angular deflection being known the intensity of the current and the temperature of the junction are deduced from pyrometric tables. These are constructed by inter-

polation when the intensities are known, which correspond to two temperatures near those to be observed.

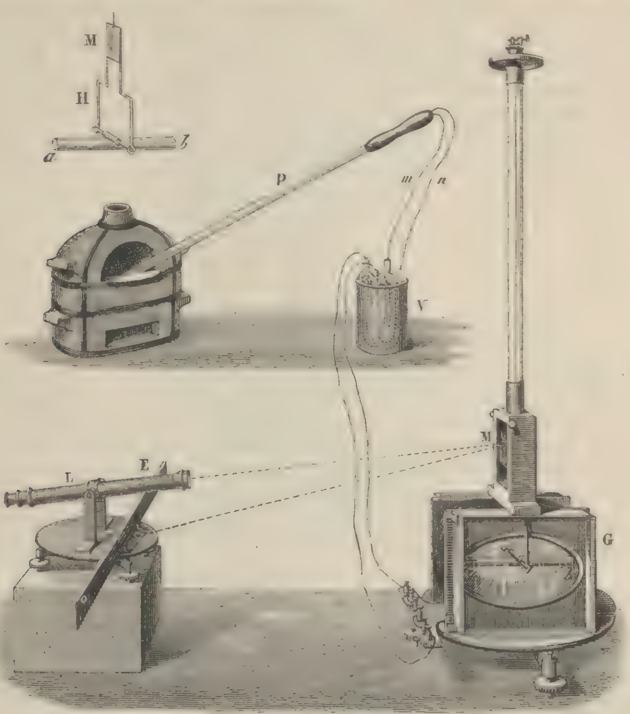


Fig. 713.

The indications of the pyrometer extend to the fusing point of the palladium.

834. **Peltier's cross.**— Peltier found that an electric current, in passing through a conductor, in some cases produces heat, in others cold. He obtained the greatest increase of temperature when the negative current passed from a good conductor of electricity to a bad one—for example, from copper to zinc ; and the least increase when the positive current passed in this direction. But when a bar of bismuth and a bar of antimony were soldered together, the temperature of the air sank at the soldering when the positive current passed from the first to the second metal, and rose in the opposite case. This experiment may easily be made by hermetically fixing in two tubulures in an air thermometer, a compound bar consisting of bismuth and antimony soldered together in such a manner that the ends project on each side. The projecting parts are provided with binding screws, so as to allow a current to be passed through. When the positive current passes from the antimony to the

bismuth, the air in the bulb is heated, it expands, and the liquid in the stem sinks; but if it passes in the opposite direction the air is cooled, it contracts, and the liquid rises in the stem. For this experiment the current must have a certain definite strength, which is found by experiment: it is best regulated by a rheostat (835).

These experiments form an interesting illustration of the principle, that whenever the effects of heat are reversed, heat is produced; and whenever the effects ordinarily produced by heat are otherwise produced, cold is the result.

CHAPTER IX.

DETERMINATION OF ELECTRICAL CONDUCTIVITY.

835. **Rheostat.**—The rheostat is an instrument by which the resistance of any given circuit can be increased or diminished without opening the circuit. As invented by Mr. Wheatstone, it consists of two parallel cylinders, one, A, of brass, the other, B, of wood (fig. 714). In the latter there is a spiral groove, which terminates at *a* in a copper ring, to which is fixed the end of a fine brass wire. This wire, which is about 40 yards long, is partially coiled on the groove; it passes to the cylinder A, and, after a great number of turns on this cylinder, is fixed at the extremity *c*. Two binding screws, *n* and *o*, connected with the battery, communicate by two steel plates; one with the cylinder A, the other with the ring *a*.

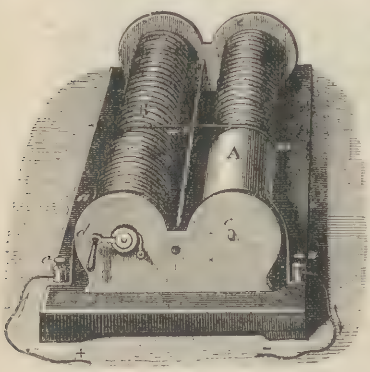


Fig. 714.

When a current enters at *o*, it simply traverses that portion of the wire rolled on the cylinder B, where the windings are insulated by the grooves; passing thence to the cylinder A, which is of metal, and in contact with the wire, the current passes directly to *m*, and thence to *n*. Hence, if the length of the current is to be increased, the handle, *d*, must be turned from right to left. If, on the contrary, it is to be diminished, the handle is to be fixed on the axis, *c*, and turning then from left to right, the wire is coiled on the cylinder A. The length of the circuit is indicated in feet and inches, by two needles, at the end of the apparatus not seen in the figure, which are moved by the cylinders A and B.

836. **Sine compass.**—This is another form of galvanometer for measuring powerful currents. Round the circular frame, M (fig. 715), several turns of stout insulated copper wire are coiled, the two ends of which, *i*,

terminate in the binding screws at E. On a table in the centre of the ring there is a magnetic needle, *m*; a second light needle, *n*, fixed to the

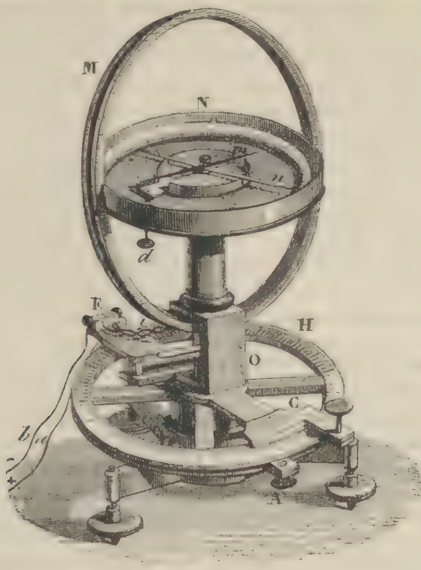


Fig. 715.

first, serves as pointer along the graduated circle N. Two copper wires, *a b*, from the sources of electricity to be measured, are connected with E. The circles M and N are supported on a foot, O, which can move about a vertical axis passing through the centre of a fixed horizontal circle, H.

The circle M being then placed in the magnetic meridian, and therefore in the same plane as the needle, the current is allowed to pass. The needles being deflected, the circuit M is turned until it coincides with the vertical plane passing through the magnetic needle *m*. The directive action of the current is now exerted perpendicularly to the direction of the magnetic needle, and it may be shown that the intensity of the current is proportional to the sine of the angle of deflection; this angle is measured on the circle H by means of a vernier on the piece C. This piece, C, fixed to the foot O, turns it by means of a knob, A. The angle of deflection, and hence its sine, being known, the intensity of the current is deduced, for this intensity is proportional to the sine.

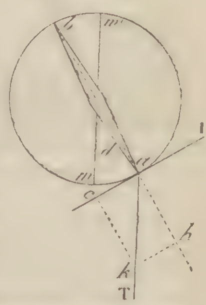


Fig. 716.

To prove this, let *mm'* be the direction of the magnetic meridian, *d* the

angle of deflection, I the intensity of the current, and T the directive action of the earth, If the direction and intensity of this latter force be represented by ak, it may be replaced by two components, ah and ac, fig. 716. . Now, as the first has no directive action on the needle, the component ac must alone counterpoise the force I, that is $I=ac$. But in the triangle, ack, $ac=ak$, cos cak, from which $ac = \mathrm{T} \sin d$, for the angle cak is the complement of the angle d, and ak is equal to T; hence lastly, $\mathrm{I} = \mathrm{T} \sin d$, which was to be proved.

837. **Determination of the resistance of a conductor. Reduced length.**—If in the circuit of a constant element a tangent compass be interposed, a certain deflection of the needle will be produced. If, then, different lengths of copper wire of the same diameter be successively interposed, corresponding deflections will in each case be produced. Let us suppose, that in a particular case the tangent of the angle of deflection (743) observed with the element and tangent compass alone was 1·88, and that when 5, 40, 70, and 100 yards of copper wire were successively placed in the circuit, the tangents of the corresponding deflections were 0·849, 0·172, 0·105, and 0·074. Now, in this experiment, the total resistance consists of two components; the resistance offered by the element and the tangent compass, and the resistance offered by the wire in each case. The former resistance may be supposed to be equal to the resistance of x yards of copper wire of the same diameter as that used, and then we have the following relations:

Length of wire.	*Tangent of angle of deflection.*
x yards	1·88
$x+5$ „	0·849
$x+40$ „	0·172
$x+70$ „	0·105
$x+100$ „	0·074

If the intensities of the currents are inversely as the resistances, that is, as the lengths of the circuits, the proportion must prevail,

$$x : x+5 = 0{\cdot}849 : 1{\cdot}886;$$

from which $x = 4{\cdot}11$. Combining, in like manner, the other observations, we get a series of numbers, the mean of which is 4·08. That is, the resistance offered by the element and galvanometer is equal to the resistance of 4·08 yards of such copper wire, and this is said to be the *reduced length* of the element and galvanometer in terms of the copper wire.

It is of great scientific and practical importance to have a *unit* or *standard of comparison* of resistances, and numerous such have been proposed. Jacobi proposed the resistance of a meter of a special copper wire a millimeter in diameter. Copper is however ill-adapted for the purpose, as it is difficult to obtain pure. Matthiessen has proposed an alloy of gold and silver, containing two parts of gold and one of silver; its conducting power is very little affected by impurities in the metals, by annealing, or by moderate changes of temperature.

Siemens' unit is a meter of pure mercury, having a section of a square millimeter. It is 0·9536 of an Ohmad or BA unit (838).

The *Varley unit*, which is used in telegraphic work, is a standard mile of a *special* copper wire $\frac{1}{16}$ of an inch in diameter. Matthiessen has proposed instead of this a mile of pure annealed copper wire $\frac{1}{16}$ in. in diameter.

838. **British Association unit of electrical resistance.**—The great importance, both theoretically and practically, of having some uniform standard for the comparison of electrical resistance has for years past engaged the attention of a committee of the British Association, which includes the principal electricians in this country. Their labours have resulted in the adoption of a standard which has received the approval of men of science both in this and other countries. The following account of this unit, which it is proposed to call the Ohmad or BA unit, has been kindly furnished by the secretary to the Committee, Mr. Fleeming Jenkin.

It represents a convenient multiple of the so-called absolute unit of electrical resistance. The word 'absolute,' as here used, does not imply accuracy of construction, but is intended to express that the measurement of electrical resistance is made by a unit which bears a definite relation to the fundamental units of time, mass, and space only; instead of being a mere comparison with the resistance of some particular piece of metal arbitrarily chosen as the unit. In a similar sense a square foot and a cubic foot may be called absolute units of surface and capacity, an acre and a gallon arbitrary units.

It seems strange at first that the unit of electrical resistance can be measured by reference to time, mass, and space only, without reference to the specific qualities of any material; but our chief knowledge of electric phenomena is derived from an observation of mechanical effects, and we need, therefore, feel no surprise at learning that those phenomena can be measured in purely mechanical units. The voltaic current, electromotive force, and resistance, quantity, and capacity, can all be so measured in more than one way. The electromagnetic measurement of current is determined by the following considerations. If f be the force exerted by a current of strength C, and length L, on a pole of a magnet; m being the magnetic strength of that pole, and K its distance from the current, it is found by experiment that f varies as $\frac{\mathrm{CL}m}{\mathrm{K}^2}$, so that $\mathrm{C} = \kappa \frac{f\mathrm{K}^2}{\mathrm{L}m}$, where κ is some constant. Now if the unit current be that which in unit length of circuit exerts unit force on a unit pole at unit distance, we get $\kappa = 1$, and the equation for C becomes

$$\mathrm{C} = \frac{f\mathrm{K}^2}{\mathrm{L}m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and C may be measured by the expression $\frac{f\mathrm{K}^2}{\mathrm{L}m}$.

Again, for the resistance we get

$$r = \frac{\mathrm{W}}{\mathrm{C}^2 t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where W is the work done in the time t by a current C flowing in a circuit of the resistance r. Now, the first equation allows us to measure a current in terms of a force f, two lengths K and L, and a magnitude m, which again depends on measurements of force and length only, so that we here have a current measured in mechanical units in virtue of a mathematical relation between the phenomena produced by the current and the mechanical units. It follows from the equation that the unit current will be that of which each unit length exerts a unit force on a unit pole at unit distance. The second equation, like the first, is deduced from observation. The resistance of a circuit is found to be proportional to the work done by a current in that circuit, and inversely proportional to the square of the current and to the time during which it acts; any two circuits for which $\frac{W}{C^2t}$ is equal have equal resistances; if this quantity for circuit A is double what it is for circuit B, then the resistance of circuit A is double that of circuit B. Therefore, we have exactly the same ground for saying that $\frac{W}{C^2t}$ measures the resistance of the circuit that we have for saying a^2 measures the contents of a square with sides equal to a. In equation 2, W, the work, is essentially a mechanical measurement, for, though generally observed in the form of heat, it is by Joule's equivalent referred to the mechanical unit of energy or work.

Moreover from Ohm's law $C = \frac{e}{r}$ . . . . (3)

further measures electromotive force in terms of C and r, and Faraday's discovery expressed by equation

$$Q = Ct,$$

where Q is the quantity of electricity conveyed by the current C in the time t, shows how quantity is measured in the same mathematical series.

Although nothing can be simpler than the mathematical conceptions here involved, the practical measurement of resistance, or any other of the above magnitudes by direct reference to force, work, time, etc., involves much labour, so that for each kind of measurement it is necessary for practical use to construct a standard which affords the desired measure by direct and simple comparison with the thing measured. Thus, a Frenchman to measure wine does not work out the cubic contents of a bottle, but measures the number of litres by reference to a standard litre, which is a simple decimal submultiple of the cubic metre. In like manner practical measurements of resistance are made by comparison with the Ohm or BA unit prepared to represent a simple decimal multiple (ten million times) the absolute electromagnetic unit; the metre, the gramme, and the second of time were taken as fundamental units by the committee, and one which is approximately equal to 10^7 metre seconds. Great care has been taken in the determination and construction of the standard, which is represented by several coils of wires of various metals and alloys, and by tubes of mercury which have all been adjusted to represent one and the same standard unit, the variety of materials being intended as a safeguard against possible alteration in resistance of one or

more of the coils or tubes. Certified copies of the unit, consisting of coils of platinum-silver wire, are issued by the Committee through their secretary, Mr. Fleeming Jenkin. Similar standards for the measurement of currents, electromotive force, quantity, and capacity will also be issued.

The Ohmad is 1·0486 of a Siemens' unit; that is, it is equal to the resistance of a prism of pure mercury 1 square millimeter in section and 1·0486 meter in length at the temperature 0°.

839. **Equivalent conductors.**—The resistance of a conductor depends, as we have seen (743), on its length, section, and conductivity. Two conductors C and C′, whose length, conductivity, and section are respectively λ λ', κ κ', ω ω', would offer the same resistance, and might be substituted for each other in any voltaic circuit, without altering its intensity, provided that $\frac{\lambda}{\kappa\omega} = \frac{\lambda'}{\kappa'\omega'}$; and such conductors are said to be *equivalent* to each other. An example will best illustrate the application of this principle.

It is required to know what length of a cylindrical copper wire 4 mm. in diameter would be equivalent to 12 yards of copper wire 1 mm. in diameter.

Let $\lambda = 12$ the length of the copper wire 1 mm. in diameter, and λ' the length of the other wire; then since in this case the material is the same, the conductivity is the same, and the equation becomes $\frac{\lambda}{\omega} = \frac{\lambda'}{\varpi'}$. Now the sections of the wires are directly as the squares of the diameters, and hence we have $\frac{12}{1^2} = \frac{\lambda'}{4^2}$, or $\lambda' = 12 \times 16 = 192$. That is, 192 yards of copper wire 4 mm. in thickness would only offer the same resistance as 12 yards of copper wire 1 mm. in thickness.

How thick must an iron wire be which for the same length shall offer the same resistance as a copper wire 2·5 mm. in diameter?

Here the length being the same, the expression becomes $\kappa\omega = \kappa'\omega'$, or since the sections are as the squares of the diameters $\kappa d^2 = \kappa' d'^2$. The conductivity of copper is unity, and that of iron 0·138. Hence we have $2{\cdot}5^2 = d'^2 \times 0{\cdot}138$ or $d'^2 = 6{\cdot}25 \div 0{\cdot}138 = 45{\cdot}3$ mm. or $d' = 6{\cdot}7$ mm. That is, any length of a copper wire 2·5 mm. in diameter might be replaced by an iron wire of the same length, provided its diameter were 6·7 mm.

840. **Determination of electrical conductivity.**—The various methods of determining the electrical conductivity of a body consist essentially in determining what length of a given section of the known body will offer the same resistance as that length of a metallic wire of a given section taken as a standard of comparison. A description of the principle of one of these methods, known as Wheatstone's Balance, will give a general idea of them.

On a base of some hard wood four stout wires are fixed, in the manner represented in figure 717. They are provided with binding screws at A, B, C, and D, and there are breaks at *a*, *b*, *c*, *d*, also provided with binding screws, so that any resistance may be introduced there. The

points A and C are connected with the terminals of a battery, while B and D are connected with a delicate galvanometer. Now it can be shown

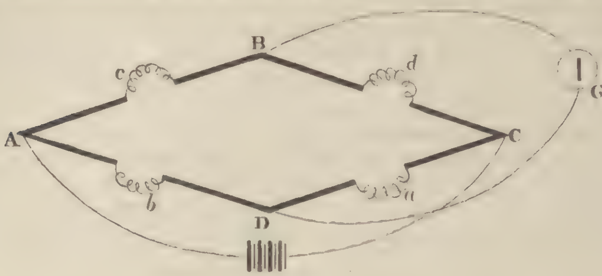


Fig. 717.

that if the resistances introduced at a, b, c, d, and which we will designate by these letters, bear a certain relation, no current will pass in the galvanometer.

Suppose first of all that the resistances are all equal in every respect; the current arriving at A would divide, one part would traverse the galvanometer in the direction AcBGD, and the other in the direction AbDGB; and as both these are equal and opposite in direction, no effect would be produced on the galvanometer ; but if the resistances a and b are different, the tensions at B and D will be different, and accordingly a current will traverse the galvanometer either from B to D or from D to B, and the needle be deflected in a corresponding manner. If now one of the resistances can be varied, if, for instance, c is a rheostat, either by increasing or diminishing the amount of wire, the two resistances may be made equal, and then a current ceases to pass. We can then express one resistance, b, in terms of c.

Wheatstone's bridge, however, is more general. It can be shown that no current passes, provided that the four resistances bear to each other the ratio $a : b = d : c$. So that if c, for instance, is the resistance to be determined, by varying the others in a suitable manner the proportion can always be obtained. In practice two of them are generally fixed resistances of known amount, and the third is a rheostat ; and, where possible, it is most convenient to take $a = b$, in which case $d = c$.

The following is a method of determining the internal resistance of an element. A circuit is formed consisting of one element, a rheostat and a galvanometer, and the intensity I is noted on the galvanometer. A second element is then joined with the first, so as to form one of double the size, and therefore half the resistance, and then by adding a length l of the rheostat wire, the intensity is brought to what it originally was. Then if E is the electromotive force, and R the resistance of an element, r, the resistance of the galvanometer and the other parts of the circuit; the intensity I in the one case is $I = \frac{E}{R + r}$, and in the other $= \frac{E}{\frac{1}{2}R + r + l}$, and since the intensity in both cases is the same, $R = 2l$.

841. **Electrical conductivity.**—We can regard conductors in two aspects, and consider them as endowed with a greater or less facility for allowing electricity to traverse them, a property which is termed *conductivity*: or we may consider conductors interposed in a circuit as offering an obstacle to the passage of electricity, that is, a resistance which it must overcome. A good conductor offers a feeble resistance, and a bad conductor a great resistance. Conductivity and resistance are the inverse of each other.

The conductivity of metals has been investigated by many physicists by methods analogous in general to that described in the preceding paragraph, and very different results have been obtained. This arises mainly from the different degrees of purity of the specimens investigated, but their molecular condition has also great influence. Matthiessen finds the difference in conductivity between hard-drawn and annealed silver wire to amount to 8·5, for copper 2·2, and for gold 1·9 per cent. The following are results of a series of careful experiments by Matthiessen on the electrical conductivity of metals at 0° C. compared with silver as a standard.

Silver	100·0	Iron	16·8
Copper	99·9	Tin	13·1
Gold	80·0	Lead	8·3
Aluminium	56·0	German Silver	7·7
Sodium	37·4	Antimony	4·6
Zinc	29·0	Mercury	1·6
Cadmium	23·7	Bismuth	1·2
Potassium	20·8	Graphite	0·07
Platinum	18·0		

The conductivity of metals is *diminished* by an increase in temperature. The law of this diminution is expressed by the formula

$$\kappa_t = \kappa_0 (1 - at + bt^2);$$

where κ_t and κ_0 are the conductivities at t and 0° respectively, and a and b are constants, which are probably the same for all pure metals. For ten metals investigated by Matthiessen he found that the conductivity is expressed by the formula

$$K_t = K_0 (1 - 0{\cdot}0037647t + 0{\cdot}00000834t^2).$$

Liquids are infinitely worse conductors than metals. The conductivity of a solution of one part of chloride of sodium in 100 parts of water is $\frac{1}{30000000}$ that of copper. In general, acids have the highest, and solutions of alkalis and neutral salts the feeblest conductivity. Yet, in solutions, the conductivity does not increase in direct proportion to the quantity of salt dissolved.

The following is a list of the conductivity of a few liquids as compared with that of pure silver.

Pure silver		100,000,000·00
Nitrate of copper, saturated solution		8·99
Sulphate of copper	ditto	5·42

Chloride of sodium	ditto . .	31·52
Sulphate of zinc	ditto . .	5·77
Sulphuric acid, 1·10 sp. gr.	. . .	99·07
" " 1·24 sp. gr.	. . .	132·75
" " 1·40 sp. gr.	. . .	90·75
Nitric acid, commercial	. . .	88·68
Distilled water	. . . . .	0·01

Liquids and fused conductors increase in conductivity by an increase of temperature. This increase is expressed by the formula

$$\kappa_t = \kappa_0 \, (1 + at),$$

and the values of a are considerable. Thus, for a saturated solution of sulphate of copper, it is 0·0286.

By most physicists the conductivity of liquids has been regarded as a purely *electrolytic* conductivity that is due to chemical decomposition. Yet Faraday, in stating his law of electrolytic decomposition, had announced that it was subject to certain restrictions in cases in which liquids could conduct electricity without being decomposed. Foucault has recently shown by delicate experiments, that liquids have a peculiar conductivity, *a physical* conductivity analogous to that of metals. This is, however, much less than the electrolytic conductivity, but may have a distinct influence on the chemical effects of currents and on Faraday's law.

842. **Determination of electromotive force. Wheatstone's method.** In the circuit of the element whose electromotive force is to be determined, a tangent compass and a rheostat are inserted, the latter being so arranged that the intensity I of the current is a definite amount; for example, the galvanometer indicates 45°. By increasing the amount of the rheostat wire by the length l, a diminished intensity i (for instance 40°) is obtained.

A second standard element is then substituted for that under trial, and by arranging the rheostat, the intensity of the current is first made equal to I, and then, by the addition of l lengths of the rheostat, is made $= i$.

Then if E and E_1 are the two electromotive forces, R and R_1 their resistances when they have the intensity I, and l and l_1 the lengths added; we have

Trial element.	Standard element.
$I = \frac{E}{R}$	$I = \frac{E_1}{R_1}$
$i = \frac{E}{R + l}$	$i = \frac{E_1}{R_1 + l_1}$

from which we have

$$E = E_1 \frac{l}{l_1}$$

Hence the electromotive forces of the elements compared are directly as the lengths of the wire interposed.

Another method is described by Wiedemann. The two elements are connected in the same circuit with a tangent galvanometer, or other apparatus for measuring intensity, first in such a manner that their currents go in the same direction, and, secondly, that they are opposed. Then if the electromotive forces are E and E′, their resistances R and R′, the other resistances in the circuits r, while I_s is the intensity when the elements are in the same direction, and I_d the intensity when they go in opposite directions, then :

$$I_s = \frac{E + E'}{R + R' + r}$$

and
$$I_d = \frac{E - E'}{R + R' + r}$$

whence
$$E' = \frac{E\,(I_s - I_d)}{I_s + I_d}$$

843. **Siemens' electrical resistance thermometer.**—Supposing in a Wheatstone's bridge arrangement, after the ratio $a : b = d : c$ has been established, the temperature of one of the coils, c, for instance, be increased, the above ratio will no longer prevail, for the resistance of c will have been altered by the temperature, and if d be the rheostat the length of wire must be altered so as to produce equivalence. On this idea Siemens has based a mode of observing the temperature of difficultly accessible places. He places a coil of known resistance in the particular locality whose temperature is to be observed; it is connected by means of long conducting wires with the place of observation, where it forms part of a Wheatstone's bridge arrangement. The resistance of the coil is known in terms of the rheostat, and by preliminary trials it has been ascertained how much additional wire must be introduced to balance a given increase in the temperature of the resistance coil. This being known, and the apparatus adjusted at the ordinary temperature, when the temperature of the resistance coil varies, this variation in either direction is at once known by observing the quantity which must be brought in or out of the rheostat to produce equivalence.

This apparatus has been of essential service in watching the temperature of large coils of telegraph wire, which, stowed away in the hold of vessels, are very liable to become heated. It might also be used for the continuous and convenient observation of underground and submarine temperatures. If a coil of platinum wire were substituted for the copper, the apparatus could be used for watching the temperature of the interior of a furnace.

844. **Derived currents.**—In fig. 718 the current from a Bunsen's element traverses the wire *rqpnm* : let us take the case in which any two points of this circuit n and q are joined by a second wire, *nxq*. The current will then divide at the point q into two others, one of which goes in the direction *qpnm*, while another takes the direction *qxnm*. The two points q and n from which the second conductor starts and ends are called the *points of derivation*, the wire *qpn* and the wire *qxn* are *derived*

wires. The currents which traverse these wires are called the *derived* or *partial currents* ; the current which travelled the circuit *rqpnm* before

Fig. 718.

it branches is the *primitive current*; and the name *principal current* is given to the whole of the new current which traverses the circuit when the derived wire has been added. The principal current is stronger than the primitive one, because the interposition of the wire *qxn* lessens the total resistance of the circuit.

If the two derived wires are of the same length and the same section, their action would be the same as if they were juxtaposed, and they might be replaced by a single wire of the same length but of twice the section, and therefore with half the resistance. Hence the current would divide into two equal parts along the two conductors.

When the two wires are of the same length but of different sections, the current would divide unequally, and the quantity which traversed each wire would be proportional to its section, just as when a river divides into two branches, the quantity of water which passes in each branch is proportional to its dimensions. Hence the resistance of the two conductors joined would be the same as that of a single wire of the same length, the section of which would be the sum of the two sections.

If the two conductors *qpn* and *qxn* are different, both in kind, length, and section, they could always be replaced by two wires of the same kind and length, with such sections that their resistances would be equal to the two conductors; in short, they might be replaced by equivalent conductors. These two wires would produce in the circuit the same effect as a single wire, which had this common length, and whose section would be the sum of the sections thus calculated. The current divides at the junction into two parts proportional to these sections, or inversely as the resistances of the two wires.

Suppose, for instance, *qpn* is an iron wire 5 metres in length, and 3 mm square in section, and *qxn* a copper wire.

The first might be replaced by a copper wire a meter in length, whose section would be $\frac{3}{5} \times \frac{1}{7}$ (taking the conductivity of copper at 7 times that of iron) or $\frac{3}{35}$ square mm. The second wire might be replaced by a copper wire a meter in length with a section of $\frac{2}{9}$ square mm. These two wires would present the same resistance as a copper wire a meter in length, and with a section of $\frac{3}{35} + \frac{2}{9} = \frac{97}{315}$ square millimeters.

The principal current would divide along the wires in two portions, which would be as $\frac{3}{35} : \frac{2}{9}$.

The principal laws of divided circuits are as follows :—

i. *The sum of the intensities in the divided parts of a circuit is equal to the intensity of the principal current.*

ii. *The intensities of the currents in the divided parts of a circuit are inversely as their resistances ; or, what is the same, the division of a current into partial currents which lie between two points is directly as the respective conductivities of these branches.*

And as problems on divided circuits frequently occur in telegraphy the following formulæ, which include these laws, are given for a simple case.

If I be the intensity of the current in the undivided part of the circuit *rqpnm*, and if i is the intensity in one branch (say in the above figure *qpn*) and i' in *qxn* ; if R r and r_1 are the corresponding resistances, the electromotive force being E, then

$$I = \frac{E\,(r + r_1)}{Rr + Rr_1 + rr_1}$$

$$i + \frac{E\,r_1}{Rr + Rr_1 + rr_1}$$

$$i = \frac{E\,r}{Rr + Rr_1 + rr_1}$$

The resistance R_4 of the whole circuit through which the current circulates is

$$R_1 = R + \frac{rr_1}{r + r_1}$$

and therefore the total resistance of the derived currents *qpn* and *qxn* is

$$\frac{rr_1}{r + r_1}$$

CHAPTER X.

ANIMAL ELECTRICITY. APPLICATION OF ELECTRICITY TO THERAPEUTICS.

845. **Peculiar current of animals.**—It has been already shown that animal electricity has been the subject of discussion between physiologists and physicists (630). Since Galvani, numerous researches have been made on this subject, especially by Aldini, Humboldt, Lehot, Marianini, and Matteucci.

By means of the galvanometer, Nobili first observed, in frogs prepared like those of Galvani (fig. 579), a current, which he named *proper current* of the frog. For this purpose he placed the crural members of the frog

in a capsule full of saline water, and then the lumbar nerves in a second capsule full of the same solution, and closed the circuit by immersing in each capsule one of the ends of a fine galvanometer wire. He thus obtained a deflection of from 10° to 30°, indicating a current from the feet to the head of the animal.

Matteucci obtained analogous effects by forming piles of the thighs of frogs. For this purpose he took the halves of the thighs laid bare, but without removing the lumbar nerve, and he arranged them one upon the other, so that each nerve rested upon the muscular part of the next following one. Closing the circuit by means of the galvanometer, he obtained, with eight halves of thighs, a deflection of 12°.

The same physicist also constructed batteries of frogs' thighs, by removing the lumbar nerve, and causing the interior of the muscle of each thigh to touch the external surface of the following thigh. In the muscles of these animals, whether living or recently killed, he always observed a current, when this circuit was closed, from the interior of the muscle to the surface. M. Mateucci calls this current the *muscular current*, to distinguish it from the *proper current* of the frog. In these animals he always met with both currents, while in other animals he observed nothing more than the muscular current.

M. Dubois-Reymond has recently published researches on the muscular currents in man. Owing to the great resistance of the human body, it was necessary to use in these researches a galvanometer with 24,000 windings. M. Dubois-Reymond observed that when the two ends of the galvanometer were connected with two symmetric parts of the body —for instance, with the two hands or the two feet—the galvanometer gave at first very irregular indications; but soon a current was produced, the direction of which was constant as often as the experiment was repeated, even at distant intervals. This current had not the same intensity at different intervals; in the same subject the direction might change, but only at distant epochs; for it often remained with a constant direction for several months.

846. **Electrical fish.**—Electrical fish are those fish which have the remarkable property of giving, when touched, shocks like those of the Leyden jar. Of these fish there are several species, the best known of which are the torpedo, the gymnotus, and the silurus. The torpedo, which is very common in the Mediterranean, has been carefully studied by MM. Becquerel and Breschet in France, and by M. Matteucci in Italy. The gymnotus has been investigated by Humboldt and Bonpland in South America, and in England by Faraday, who had the opportunity of examining live specimens.

The shock which they give serves both as a means of offence and of defence. It is purely voluntary, and becomes gradually weaker as it is repeated and as these animals lose their vitality, for the electrical action soon exhausts them materially.

The shock is very violent. According to Faraday the shock which the gymnotus gives is equal to that of a battery of 15 jars exposing a

coating of 25 square feet, which explains how it is that horses frequently give way under the repeated attacks of the gymnotus.

Numerous experiments show that these shocks are due to ordinary electricity. For if, touching with one hand the back of the animal, the belly is touched with the other, or with a metal rod, a violent shock is felt in the wrists and arms; while no shock is felt if the animal is touched with an insulating body. Further, when the back is connected with one end of a galvanometer wire and the belly with the other, at each discharge the needle is deflected, but immediately returns to zero, which shows that there is an instantaneous current; and, moreover, the direction of the needle shows that the current goes from the back to the belly of the fish. Lastly, if the current of a torpedo be passed through a helix, in the centre of which is a small steel bar, the latter is magnetised by the passage of the discharge.

By means of the galvanometer, Matteucci has established the following facts:

1. When a torpedo is lively, it can give a shock in any part of its body; but as its vitality diminishes, the parts at which it can give a shock are nearer the organ which is the seat of the development of electricity.

2. Any point of the back is always positive as compared with the corresponding point of the belly.

3. Of any two points at different distances from the electrical organ, the nearest always plays the part of positive pole, and the furthest that of negative pole. With the belly, the reverse is the case.

The organ where the electricity is produced in the torpedo is double, and formed of two parts symmetrically situated on the two sides of the head, and attached to the skull bone by the internal face. These two parts unite in front of the nasal bones, but are separated from the skin by a strong aponeurosis. According to Matteucci, each of these organs consists of a tolerably large number of small prismatic masses, placed side by side, and proceeding from the external to the internal face, so that a section perpendicular to the apex of the prism appears like the cells of a honeycomb. These prisms, perpendicular to their summits, are divided by diaphragms, forming a series of small cells which are filled with a liquid consisting essentially of 9 parts of water to 1 of albumen and a little common salt.

Reasoning from the following experiment, Matteucci considers each of these vesicles as the elementary organ of the electrical apparatus. He removed from the apparatus of the torpedo a mass of these vesicles of the size of a pin's head, and put it in contact with the nerves of a dead frog prepared in Galvani's manner. When this mass was excited by pricking it with a pin, contractions were observed in the frog.

Matteucci investigated further the influence of the brain on the discharge. For this purpose he laid bare the brain of a living torpedo, and found that the first three lobes could be irritated without the discharge being produced, and that when they were removed the animal still possessed the faculty of giving a shock. The fourth lobe, on the contrary,

could not be irritated without an immediate production of the discharge: but if it was removed, all disengagement of electricity disappeared, even if the other lobes remained untouched. Hence it would appear that the primary source of the electricity elaborated is the fourth lobe, whence it is transmitted by means of the nerves to the two organs described above, which act as multipliers. In the silurus the head appears also to be the seat of the electricity; but in the gymnotus it is found in the tail.

Reasoning from this considerable disengagement of electricity in the case of certain fish, physicists have inquired whether a similar elaboration of electricity does not take place in other animals: not perhaps in sufficient quantity to produce shocks like those of the Leyden jar, but sufficiently so to effect slow actions, and to serve for the essential functions of life, like the secretions, digestion, etc.

847. **Application of electricity to medicine.**—The first applications of electricity to medicine date from the discovery of the Leyden jar. Nollet and Boze appear to have been the first who thought of the application, and soon the spark and electrical frictions became a universal panacea; but it must be admitted that subsequent trials did not come up to the hopes of the experimentalists.

After the discovery of dynamic electricity Galvani proposed its application to medicine; since which time many physicists and physiologists have been engaged upon this subject, and yet there is still much uncertainty as to the real effects of electricity, the cases in which it is to be applied, and the best mode of applying it. Practical men prefer the use of currents to that of statical electricity, and, except in a few cases, discontinuous to continuous currents. There is, finally, a choice between the currents of the battery and those of induction currents; further, the effects of the latter differ, according as induction currents of the first or second order are used.

In fact, since induction currents, although very intense, have a very feeble chemical action, it follows that when they traverse the organs, they do not produce the chemical effects of the current of the battery, and hence do not tend to produce the same disorganisation. Further, in electrifying the muscles of the face, induction currents are to be preferred, for Dr. Duchenne has found that these currents only act feebly on the retina, while the currents of the battery act energetically on this organ, and may affect it dangerously, as serious accidents have shown. There is a difference in the action of induced currents of different orders; for while the primary induced current causes lively muscular actions, but has little action on the cutaneous sensibility, the secondary induced current, on the contrary, increases the cutaneous sensibility to such a point, that its use ought to be proscribed to persons whose skin is very irritable.

Hence electrical currents should not be applied in therapeutics without a thorough knowledge of their various properties. They ought to be used with great prudence, for their continued action may produce serious accidents. Matteucci, in his lectures on the physical phenomena of living

bodies, expresses himself as follows : 'In commencing, a feeble current must always be used. This precaution now seems to me the more important, as I did not think it so before seeing a paralytic person seized with almost tetanic convulsions under the action of a current formed of a single element. Take care not to continue the application too long, especially if the current is energetic. Rather apply a frequently-interrupted current than a continuous one, especially if it be strong ; but after 20 or 30 shocks at most, let the patient take a few moments' rest.

ELEMENTARY OUTLINES

OF

METEOROLOGY AND CLIMATOLOGY.

METEOROLOGY.

848. **Meteorology.**—The phenomena which are produced in the atmosphere are called *meteors*; and *meteorology* is that part of physics which is concerned with the study of these phenomena.

A distinction is made between *aerial* meteors, such as winds, and hurricanes, and whirlwinds; *aqueous* meteors, comprising fogs, clouds, rain, dew, snow, and hail; and *luminous* meteors, as lightning, the rainbow, the aurora borealis.

Aerial Meteors.

849. **Direction and velocity of winds.**—*Winds* are currents moving in the atmosphere with variable directions and velocities. There are eight principal directions in which they blow; *north*, *north-east*, *east*, *south-east*, *south*, *south-west*, *west*, and *north-west*. Mariners further divide each of the distances between these eight directions into four others, making in all 32 directions, which are called *points* or *rhumbs*. A figure of these 32 rhumbs on a circle, in the form of a star, is known as the *mariner's card*.

The direction of the wind is determined by means of vanes, and its velocity by means of the *anemometer*. There are several forms of this instrument; the most usual consists of a small vane with fans, which the wind turns; the velocity is deduced from the number of turns made in a given time, which is measured by means of an endless screw and wheelwork. In our climate the mean velocity is from 18 to 20 feet in a second. With a velocity of 6 or 7 feet, the wind is moderate; with 30 or 35 feet, it is fresh; with 60 or 70 feet, it is strong; with a velocity of 85 to 90 feet, it is a tempest; and, from 90 to 120, it is a hurricane.

We have but few experimental results as to the law of the intensity of the force which wind exerts on surfaces exposed to its action. Smeaton gives a table compiled by Rouse from a considerable number of facts and experiments; he observes that these experiments do not deserve as much confidence for velocities above as for velocities below 50 miles an

hour. The numerical values for the pressures given, this table seems to have been calculated on the supposition that the pressure is proportional to the square of the velocity of the wind; they are approximately given by the formula

$$f = 0{\cdot}002214\ V^2,$$

where V being the velocity of the wind in feet per second, f is the pressure in pounds per square foot.

850. **Causes of winds.**—Winds are produced by the disturbance of the equilibrium in some part of the atmosphere, a disturbance always resulting from a difference in temperature between adjacent countries. Thus, if the temperature of a certain extent of ground becomes higher, the air in contact with it becomes heated, it expands and rises towards the higher regions of the atmosphere; whence it flows, producing winds which blow from hot to cold countries. But at the same time the equilibrium is destroyed at the surface of the earth, for the barometric pressure on the colder adjacent parts is greater than on that which has been heated, and hence a current will be produced with a velocity dependent on the difference between these pressures; thus two distinct winds will be produced, an upper one setting *outwards* from the heated region, and a lower one setting *inwards* towards it.

851. **Regular, periodical, and variable winds.**—According to the more or less constant directions in which winds blow, they may be classed as regular, periodical, and variable winds.

i. *Regular winds* are those which blow all the year through in a virtually constant direction. These winds, which are also known as the *trade winds*, are uninterruptedly observed far from the land in equatorial regions, blowing from the north-east to the south-west in the northern hemisphere, and from the south-east to the north-west in the southern hemisphere. They prevail on the two sides of the equator as far as 30° of latitude, and they blow in the same direction as the apparent motion of the sun, that is, from east to west.

The air above the equator being gradually heated, rises as the sun passes round from east to west, and its place is supplied by the colder air from the north or south. The direction of the wind, however, is modified by this fact, that the velocity which this colder air has derived from the rotation of the earth, namely the velocity of the surface of the earth at the point from which it started, is less than the velocity of the surface of the earth at the point at which it has now arrived; hence the currents acquire, in reference to the equator, the constant direction which constitutes the trade winds.

ii. *Periodical winds* are those which blow regularly in the same direction at the same seasons, and at the same hours of the day: the monsoon, simoom, and the land and sea breeze are examples of this class. The name *monsoon* is given to winds which blow for six months in one direction, and for six months in another. They are principally observed in the Red Sea and in the Arabian Gulf, in the Bay of Bengal and in the Chinese Sea. These winds blow towards the continents in summer, and in a contrary direction in winter. The *simoom* is a hot wind which blows

over the deserts of Asia and Africa, and which is characterised by its high temperature and by the sands which it raises in the atmosphere and carries with it. During the prevalence of this wind the air is darkened, the skin feels dry, the respiration is accelerated, and a burning thirst is experienced.

This wind is known under the name of *sirocco* in Italy and Algiers, where it blows from the great desert of Sahara. In Egypt, where it prevails from the end of April to June, it is called *kamsin*. The natives of Africa, in order to protect themselves from the effects of the too rapid perspiration occasioned by this wind, cover themselves with fatty substances.

The *land* and *sea breeze* is a wind which blows on the sea coast during the day from the sea towards the land, and during the night from the land to the sea. For during the day the land becomes more heated than the sea, in consequence of its lower specific heat and greater conductivity, and hence as the superincumbent air becomes more heated than that upon the sea, it ascends and is replaced by a current of colder and denser air flowing from the sea towards the land. During the night the land cools more rapidly than the sea, and hence the same phenomenon is produced in a contrary direction. The sea breeze commences after sunrise, increases to three o'clock in the afternoon, decreases towards evening, and is changed into a land breeze after sunset. These winds are only perceived at a slight distance from the shores. They are regular in the tropics, but less so in our climates; and traces of them are seen as far as the coasts of Greenland. The proximity of mountains also gives rise to periodical daily breezes.

iii. *Variable winds* are those which blow sometimes in one direction and sometimes in another, alternately, without being subject to any law. In mean latitudes the direction of the winds is very valuable; towards the poles this irregularity increases, and under the arctic zone the winds frequently blow from several points of the horizon at once. On the other hand, in approaching the torrid zone, they become more regular. The south-west wind prevails in the north of France, in England, and in Germany; in the south of France the direction inclines towards the north, and in Spain and Italy the north wind predominates.

852. **Law of the rotation of winds.**—Spite of the great irregularity which characterises the direction of the winds in our latitude, it has been ascertained that the wind has a preponderating tendency to veer round according to the sun's motion, that is, to pass from north, through north-east, east, south-east to south, and so on round in the same direction from west to north; that it often makes a complete circuit in that direction, or more than one in succession, occupying many days in doing so, but that it rarely veers, and very rarely or never makes a complete circuit in the opposite direction.

For a station in south latitude a contrary law of rotation prevails.

This law, though more or less suspected for a long time, was first formerly enunciated and explained by Dove, and is known as *Dove's law of rotation of winds.*

853. **Fogs and mists.**—When aqueous vapours rising from a vessel of boiling water, diffuse in the colder air, they are condensed; a sort of cloud is formed which consists of a number of small hollow vesicles of water, which remain suspended in the air. These are usually spoken of as vapours, yet they are not so, at any rate not in the physical sense of the word; for they are partially condensed vapours.

When this condensation of aqueous vapours is not occasioned by contact with cold solid bodies, but takes place throughout large spaces of the atmosphere, they constitute *fogs* or *mists*, which, in fact, are nothing more than the appearance seen over a vessel of hot water.

A chief cause of fogs consists in the moist soil being at a higher temperature than the air. The vapours which then ascend condense and become visible. In all cases, however, the air must have reached its point of saturation before condensation takes place. Fogs may also be produced when a current of hot and moist air passes over a river at a lower temperature than its own, for then the air being cooled, as soon as it is saturated, the excess of vapour present is condensed.

The distinction between mists and fogs is one of degree rather than of kind. A fog is a very thick mist.

854. **Clouds.**—*Clouds* are masses of vapour, condensed into little drops or vesicles of extreme minuteness, like fogs; from which they only differ in occupying the higher regions of the atmosphere; they always result from the condensation of vapours which rise from the earth. According

Fig. 719.

to their appearance, they have been divided by Howard into four principal kinds: the *nimbus*, the *stratus*, the *cumulus*, and the *cirrus*. These

four kinds are represented in fig. 719, and are designated respectively by one, two, three, and four birds on the wing.

The *cirrus* consist of small whitish clouds, which have a fibrous or wispy appearance, and occupy the highest regions of the atmosphere. The name of *mares' tails*, by which they are generally known, well describes their appearance. From the low temperature of the spaces which they occupy, it is more than probable that cirrus clouds consist of frozen particles ; and hence it is that haloes, coronæ, and other optical appearances, produced by refraction and reflection from ice crystals, appear almost always in these clouds and their derivatives. Their appearance often precedes a change of weather.

The *cumulus* are rounded spherical forms which look like mountains piled one on the other. They are more frequent in summer than in winter, and after being formed in the morning, they generally disappear towards evening. If, on the contrary, they become more numerous, and especially if surmounted by cirrus clouds, rain or storms may be expected.

Stratus clouds consist of very large and continuous horizontal sheets, which chiefly form at sunset, and disappear at sunrise. They are frequent in autumn and unusual in spring time, and are lower than the preceding.

The *nimbus*, or rain clouds, which are sometimes classed as one of the fundamental varieties, are properly a combination of the three preceding kinds. They affect no particular form, and are solely distinguished by a uniform grey tint, and by fringed edges. They are indicated on the right of the figure by the presence of one bird.

The fundamental forms pass into one another in the most varied manner; Howard has classed these traditional forms as *cirro-cumulus*, *cirro-stratus*, and *cumulo-stratus*, and it is often very difficult to tell from the appearance of a cloud which type it most resembles. The cirro-cumulus is most characteristically known as a 'mackerel sky ;' it consists of small roundish masses, disposed with more or less irregularity and connection. It is frequent in summer, and attendant on warm and dry weather. *Cirro-stratus* appears to result from the subsidence of the fibres of cirrus to a horizontal position, at the same time approaching laterally. The form and relative position when seen in the distance frequently give the idea of shoals of fish. The tendency of *cumulo-stratus* is to spread, settle down into the *nimbus*, and finally fall as rain.

The height of clouds varies greatly ; in the mean it is from 1,300 to 1,500 yards in winter, and from 3,300 to 4,400 yards in summer. But they often exist at greater heights; Gay-Lussac, in his balloon ascent, at a height of 7,650 yards, observed cirrus-clouds above him, which appeared still to be at a considerable height. In Ethiopia, M. d' Abbadie observed storm clouds whose height was only 230 yards above the ground.

In order to explain the suspension of clouds in the atmosphere, Halley first proposed the hypothesis of vesicular vapours. He supposed that clouds are formed of an infinity of extremely minute vesicles, hollow,

like soap bubbles filled with air, which is hotter than the surrounding air; so that these vesicles float in the air like so many small balloons. This theory, which was first propounded by Saussure, has been defended by Kratzenstein, subsequently by Bravais and most physicists; it has, however, been combated by Desagueliers, and afterwards by Monge, and has at present many opponents. These latter assume that clouds and fogs consist of extremely minute droplets of water, which are retained in the atmosphere by the ascensional force of currents of hot air, just as light powders are raised by the wind. Ordinarily, clouds do not appear to descend, but this absence of downward motion is only apparent. In fact, clouds do usually fall slowly, but then the lower part is continually dissipated on coming in contact with the lower and more heated layers; at the same time the upper part is always increasing from the condensation of new vapours; so that from these two actions clouds appear to retain the same height.

855. **Formation of clouds.**—Many causes may concur in the formation of clouds. i. The low temperature of the higher region of the atmosphere. For, owing to the solar radiation, vapours are constantly disengaged from the earth and from the waters, which from their elastic force and lower density rise in the atmosphere; meeting there continually colder and colder layers of air, they sink to the point of saturation, and then condensing in infinitely small droplets, they give rise to clouds.

ii. The hot and moist currents of air rising during the day undergo a gradually feebler pressure, and thus is produced an expansion which is a source of intense cold, and produces a condensation of vapour. Hence it is that high mountains, stopping the aerial currents, and forcing them to rise, are an abundant source of rain.

iii. A hot, moist current of air mixing with a colder current, undergoes a cooling, which brings about a condensation of the vapour. Thus the hot and moist winds of the south and south-west, mixing with the colder air of our latitude, give rain. The winds of the north and north-east tend also, in mixing with our atmosphere, to condense the vapours; but as these winds, owing to their low temperature, are very dry, the mixture rarely attains saturation, and generally gives no rain.

The formation of clouds is thus explained by Hutton. The tension of aqueous vapour, and therewith the quantity present in a given space when saturated, diminishes according to a geometric progression, while the temperature falls in arithmetical progression, and therefore the elasticity of the vapour present at any time is reduced by a fall of temperature more rapidly than in direct proportion to the fall. Hence if a current of warm air, saturated with aqueous vapour, meet a current of cold air also saturated, the air acquires the mean temperature of the two, but can only retain a portion of the vapour in the invisible condition, and a cloud or mist is formed. Thus suppose a cubic meter of air at 10° C. mixes with a cubic meter of air at 20° C., and that they are respectively saturated with aqueous vapour. By formula (297) it is easily calculated that the weight of water contained in the cubic meter of air at 10° C. is 9·397 grammes,

and in that at 20° C. is 17·632 grammes or 27·029 grammes in all. When mixed they produce two cubic meters of air at 15° C.; but as the weight of water required to saturate this is only $2 \times 12{\cdot}8 = 25{\cdot}6$ grammes, the excess, 1·429 grammes, will be deposited in the form of mist or clouds.

856. **Rain.**—When by the constant condensation of aqueous vapour the individual vapour vesicles become larger and heavier, and when finally individual vesicles unite, they form regular drops, which fall as *rain.*

The quantity of rain which falls annually in any given place, or the annual rainfall, is measured by means of a *rain gauge* or *pluviometer.* Ordinarily it consists of a cylindrical vessel M (figs. 720 and 721), closed

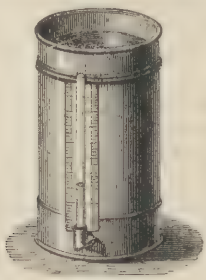


Fig. 720.

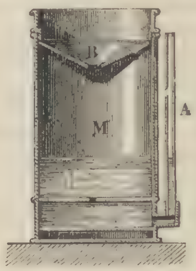


Fig. 721.

at the top by a funnel-shaped lid, in which there is a very small hole, through which the rain falls. At the bottom of the vessel is a glass tube A, in which the water rises to the same height as inside the rain gauge, and is measured by a scale on the side, as shown in the figures.

The apparatus being placed in an exposed situation, if at the end of a month the height of water in the tube is 2 inches for example, it shows that the water has attained this height in the vessel; and, consequently, that a layer of two inches in depth expresses the quantity of rain which this extent of surface has received.

It has been noticed that the quantity of rain indicated by the rain-gauge is greater as this instrument is nearer the ground. This has been ascribed to the fact that the rain-drops, which are generally colder than the layers of air which they traverse, condense the vapour in these layers, and, therefore, constantly increase in volume. Hence more rain falls on the surface of the ground than at a certain height. But it has been objected that the excess of the quantity of rain which falls, over that at a certain height, is six or seven times that which could arise from condensation, even during the whole course of the rain-drops from the clouds to the earth. The difference must, therefore, be ascribed to purely local causes, and it is now assumed that the difference arises from eddies produced in the air about the rain gauge, which are more perceptible as it is higher above the ground; as these eddies disperse the drops which would otherwise fall into the instrument, they diminish the quantity of water which it receives.

In any case it is clear that if rain-drops traverse moist air, they will from their temperature condense vapour and increase in volume. If, on the contrary, they traverse dry air, the drops tend to vaporise, and less rain falls than at a certain height; it might even happen that the rain did not reach the earth.

Many local circumstances may affect the quantity of rain which falls in different countries; but, other things being equal, most rain falls in hot climates, for there the vaporisation is most abundant. The rain-fall decreases, in fact, from the equator to the poles. At London it is 23·5 inches; at Bordeaux it is 25·8; at Madeira it is 27·7; at Havannah it is 91·2, and at St. Domingo it is 107·6. The quantity varies with the seasons; in Paris, in winter, it is 4·2 inches; in spring 6·9; in summer 6·3, and in autumn 4·8 inches. The heaviest annual rain-fall at any place in the globe is on the Khasia Hills in Bengal, where it is 600 inches; of which 500 inches fall in seven months.

The driest recorded place in England is Lincoln, where the mean rainfall is 20 inches, and the wettest is Stye, at the head of Borrowdale in Cumberland, where it amounts to 165 inches.

An inch of rain on a square yard of surface expresses a fall of 46·74 pounds, or 4·67 gallons. On an acre it corresponds to 22,622 gallons, or 100·9935 tons. 100 tons per inch per acre is a ready way of remembering this.

857. **Waterspouts.**—These are masses of vapour suspended in the lower layers of the atmosphere which they traverse, and endowed with a gyratory motion rapid enough to uproot trees, upset houses, and break and destroy everything with which they come in contact.

These meteors, which are generally accompanied by hail and rain, often emit lightning and thunder, producing the sound of carriages rolling over a stony road. Many of them have no gyratory motion, and about a quarter of those observed are produced in a calm atmosphere.

When they take place on the sea they present a curious phenomenon. The water is disturbed, and rises in the form of a cone, while the clouds are depressed in the form of an inverted cone; the two cones then unite and form a continuous column from the sea to the clouds (fig. 722), which are called *waterspouts.* Even, however, on the high seas the water of these waterspouts is never salt, proving that they are formed of condensed vapours, and not of sea water raised by aspiration.

The origin of these is not known. Kæmtz assumes that they are due principally to two opposite winds which pass by the side of each other, or to a very high wind which prevails in the higher regions of the atmosphere. Peltier and many others ascribe to them an electrical origin.

858. **Influence of aqueous vapour on climate.**—One of the most important elements in meteorology is undoubtedly the property possessed by aqueous vapour of powerfully absorbing and radiating heat. The same physicist who discovered this property (336), has applied it to the explanation of some obscure points in meteorological science, and there can be no doubt that the knowledge of it will gradually lead to a clearer

understanding of many inexplicable and apparently capricious meteorological phenomena.

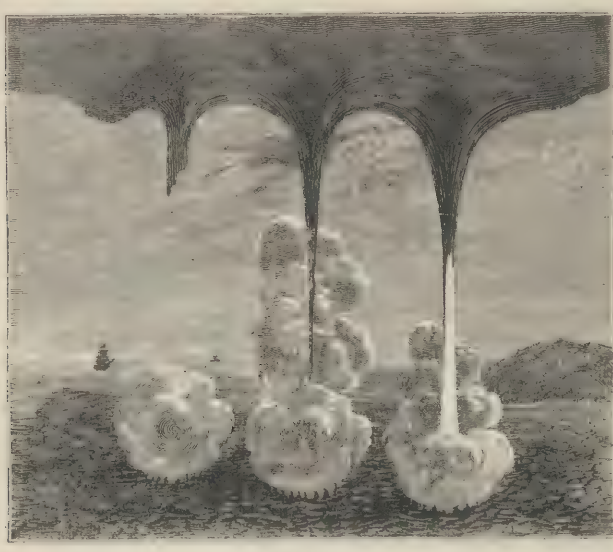


Fig. 722.

Tyndall has established the fact, that in a tube 4 feet long the atmospheric vapour on a day of average dryness absorbs 10 per cent. of obscure heat. With the earth warmed by the sun, as a source, there can be no doubt that at the very least 10 per cent. of its heat is intercepted within 10 feet of the surface. If aqueous vapour be compared atom for atom with air, its power of absorption and radiation is more than 16,000 times that possessed by air. Such facts as these are sufficient to show the importance of the small quantity of this vapour that exists in our atmosphere.

The *radiative* power of aqueous vapour may be the main cause of the torrential rains that occur in the tropics, and also of the formation of cumuli clouds in our own latitudes. It is this same property which probably causes the descent of a very fine rain, called *sérein*. This small rain has more the characteristics of falling dew, as it appears a short time after sunset, when the sky is clear; its production has therefore been attributed to the cold, resulting from the radiation of the air. It is not the air, however, but the aqueous vapour in the air, which by its own radiation chills itself, so that it condenses into *sérein*.

The *absorbent* power of aqueous vapour is even of greater importance. Whenever the air is dry, terrestrial radiation at night is so rapid as to cause intense cold. Thus, in the central parts of Asia, Africa, and Australia, the daily range of the thermometer is enormous; in the interior of the last continent a difference in temperature of no less than 40° C. has

been recorded within 24 hours. In India, and even in Sahara, owing to the copious radiation, ice has been formed at night. But the heat which aqueous vapour absorbs most largely is of the kind emitted from sources of low temperature: it is to a large extent transparent to the heat emitted from the sun, whilst it is almost opaque to the heat radiated from the earth. Consequently, the solar rays penetrate our atmosphere with a loss, as estimated by Pouillet, of only 25 per cent., when directed vertically downwards, but after warming the earth they cannot retraverse the atmosphere. Through thus preventing the escape of terrestrial heat, the aqueous vapour in the air moderates the extreme chilling which is due to the unchecked radiation from the earth, and raises the temperature of that region over which it is spread. Tyndall has thus described the action of this substance:—'Aqueous vapour is a blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer night the aqueous vapour from the air which overspreads this country, and every plant capable of being destroyed by a freezing temperature would perish. The warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost.'

859. **Tyndall's researches.**—Tyndall has recently examined the action of solar and of the electric light on vapours at a great degree of attenuation; and has found that under these circumstances they are decomposed. This new reaction not only puts a most potent agent of chemical decomposition into the hands of chemists, which remains for them to make use of, but it has led Professor Tyndall to important conclusions regarding the origin of the blue colour of the sky, and the polarisation of daylight.

For these experiments he used a glass tube with glass ends, such as he had used for his researches on radiant heat, and which is known as 'the experimental tube.' This could be exhausted and then filled with air charged with the vapours of volatile liquids, by allowing the air to pass through small Wolff bottles containing them. By mixing with different proportions of pure air the air charged with vapour, and by varying the degree of exhaustion, it was possible to have a vapour under any degree of attenuation. It was also possible to fill the tube with the vapour of a liquid alone.

The tube having been filled with air charged with vapours of nitrite of amyle, a somewhat convergent beam from the electric lamp was passed into the tube. For a moment the tube appeared optically empty, but suddenly a shower of liquid spherules was precipitated on the path of the beam forming a luminous white cloud. The nature of the substance thus precipitated was not specially investigated.

This effect was not due to any chemical action between the vapour and the air, for when either dry oxygen or dry hydrogen was used instead of air, or when the vapour was admitted alone, the effect was substantially the same. Nor was it due to any heating effect, for the beam had been previously sifted by passing through a solution of alum, and through the thick glass of the lens. The unsifted beam produced the same effect; the obscure calorific rays did not seem to interfere with the result.

The sun's light also effects the decomposition of the nitrite of amyle vapour; and this decomposition was found to be mainly due to the more refrangible rays.

When the electric light, before entering the experimental tube, was made to pass through a layer of the liquid nitrite of amyle an eighth of an inch in thickness, the luminous effect was not appreciably diminished, but the chemical action was almost entirely stopped. Thus that special constituent of the luminous radiation which effects the decomposition of the vapour is absorbed by the liquid. The liquid nitrite of amyle is probably decomposed by light; but its decomposition, if it take place at all, is far less rapid and distinct than that of the vapour. The circumstance that the absorption is the same whether the nitrite is in the liquid or in the vaporous state, is considered by Tyndall as a proof that the absorption is not the act of the molecule as a whole, but that it is atomic, that is, that it is to the atoms that the peculiar rate of vibration is transferred, which brings about the decomposition of the body.

Besides nitrite of amyle, the vapour of a number of other substances was examined, such, for example, as benzole, iodide of allyle, bisulphide of carbon. By varying the nature of the vapour the shape of a cloud could be greatly varied, and in many cases presented the most fantastic and beautiful forms.

It was also found that a vapour which when alone resists the action of light, may, by being associated with another gas or vapour, exhibit a vigorous or even violent action.

Thus, when the tube was filled with atmospheric air, mixed with nitrite of butyle vapour, the electric light produced very little effect. But with half an atmosphere of this mixture, and half an atmosphere of air which had passed through hydrochloric acid, the action of the light was almost instantaneous. In another case mixed air and nitrite of butyle vapour was passed into the tube so as to depress the barometer the $\frac{1}{10}$ of an inch; that is, the mixed air and vapour were under a pressure of $\frac{1}{300}$ of an atmosphere. Air passed through solution of hydrochloric acid was introduced until the pressure was 3 inches. The condensed beam passed through for some time without change, but afterwards a superbly blue cloud was formed.

In cases where the vapours are under a sufficient degree of attenuation, whatever otherwise be their nature, the visible action commences with the formation of a *blue cloud*. The term cloud, however, must not be understood in its ordinary sense; the blue cloud is invisible in ordinary daylight, and to be seen must be surrounded by darkness, *it alone* being illuminated by a powerful beam of light. The blue cloud differs in many important particulars from the finest ordinary clouds, and may be considered to occupy an intermediate position between these clouds and true cloudless vapour.

By graduating the quantity of vapour, the precipitation may be obtained of any required degree of fineness: forming either particles distinguishable by the naked eye, or particles beyond the reach of the highest microscopic power. There is no reason to doubt that particles

may be thus obtained whose wave-length is but a very small fraction of the length of a wave of violet light.

The case is similar to that of carbonic acid gas, which, diffused in the atmosphere, resists the decomposing action of solar light, but when in contiguity with the chlorophyle in the leaves of plants is decomposed.

When the blue cloud produced in these experiments was examined by any polarising arrangement, the light emitted laterally from the beam—that is, in a direction at right angles to its axis—was found to be perfectly polarised. This phenomenon was observed in its greatest perfection the more perfect the blue of the sky. It is produced by any particles provided they are sufficiently fine.

This is quite analogous to the light of the blue sky. When this is examined by a Nicoli prism, or any other analyser, it is found that the light, emitted at right angles to the path of the sun's rays, is polarised.

These two phenomena, the fundamental blue, and the polarisation of the sky light, which have long been the enigmas of meteorologists, find their definite solution in these experiments. We have only to assume the existence in the higher regions of the atmosphere of excessively fine particles of water ; for particles of any kind produce this effect. It is not difficult to conceive the existence of such particles in the higher regions, even on a hot summer's day. For the vapour must there be in a state of extreme attenuation ; and inasmuch as the oxygen and hydrogen of the atmosphere behave like a vacuum to radiant heat, the extremely attenuated particles of aqueous vapour are practically in contact with the absolute cold of space.

'Suppose the atmosphere surrounded by an envelope impervious to light, but with an aperture on the sunward side, through which a parallel beam of solar light could enter and traverse the atmosphere. Surrounded on all sides by air not directly illuminated, the track of such a beam would resemble that of the parallel beam of the electric light through an incipient cloud. The sunbeam would be blue, and it would discharge light laterally in the same condition as that discharged by the incipient cloud. The azure revealed by such a beam would be to all intents and purposes a blue cloud.'

860. **Dew. Hoar frost.**—*Dew* is merely aqueous vapour which has condensed on bodies during the night in the form of minute globules. It is occasioned by the chilling which bodies near the surface of the earth experience in consequence of nocturnal radiation. Their temperature having then sunk several degrees below that of the air, it frequently happens, especially in hot seasons, that this temperature is below that at which the atmosphere is satuated. The layer of air which is immediately in contact with the chilled bodies, and which virtually has the same temperature, then deposits a portion of the vapour which it contains ; just as when a bottle of cold water is brought into a warm room, it becomes covered with moisture, owing to the condensation of aqueous vapour upon it.

According to this theory, which was first propounded by Dr. Wells, all causes which promote the cooling of bodies increase the quantity of dew.

These causes are the emissive power of bodies, the state of the sky, and the agitation of the air. Bodies which have a great radiating power more readily become cool, and therefore ought to condense more vapour. In fact, there is generally no deposit of dew on metals, whose radiating power is very small, especially when they are polished ; while the ground, sand, glass, and plants, which have a great radiating power, become abundantly covered with dew.

The state of the sky also exercises a great influence on the formation of dew. If the sky is cloudless, the planetary spaces send to the earth an inappreciable quantity of heat, while the earth radiates very considerably, and therefore becoming very much chilled, there is an abundant deposit of dew. But if there are clouds, as their temperature is far higher than that of the planetary spaces, they radiate in turn towards the earth, and as bodies on the surface of the earth only experience a feeble chilling, no deposit of dew takes place.

Wind also influences the quantity of vapour deposited. If it is feeble, it increases it, inasmuch as it renews the air ; if it is strong, it diminishes it, as it heats the bodies by contact, and thus does not allow the air time to become cooled. Finally, the deposit of dew is more abundant according as the air is moister, for then it is nearer its point of saturation.

Hoar frost and *rime* are nothing more than dew which has been deposited on bodies cooled below zero, and has therefore become frozen. The flocculent form which the small crystals present, of which rime is formed, shows that the vapours solidify directly without passing through the liquid state. Hoar frost, like dew, is formed on bodies which radiate most, such as the stalks and leaves of vegetables, and is chiefly deposited on the parts turned towards the sky.

861. **Snow. Sleet.**—*Snow* is water solidified in stellate crystals, variously modified, and floating in the atmosphere. These crystals arise from the congelation of the minute vesicles which constitute the clouds, when the temperature of the latter is below zero. They are more regular when formed in a calm atmosphere. Their form may be investigated by collecting them on a black surface, and viewing them through a strong lens. The regularity, and at the same time variety, of their forms are truly beautiful. Fig. 723 shows some of the forms as seen through a microscope.

It snows most in countries near the poles, or which are high above the sea level. Towards the poles, the earth is constantly covered with snow ; the same is the case on high mountains, where there are perpetual snows even in equatorial countries.

Sleet is also solidified water, and consists of small icy needles pressed together in a confused manner. Its formation is ascribed to the sudden congelation of the minute globules of the clouds in an agitated atmosphere.

862. **Hail.**—*Hail* is a mass of compact globules of ice of different sizes, which fall in the atmosphere. In our climate hail falls principally during spring and summer, and at the hottest times of the day : it rarely falls at night. The fall of hail is always preceded by a peculiar noise.

Hail is generally the precursor of storms, it rarely accompanies them, and follows them more rarely still. Hail falls from the size of small peas

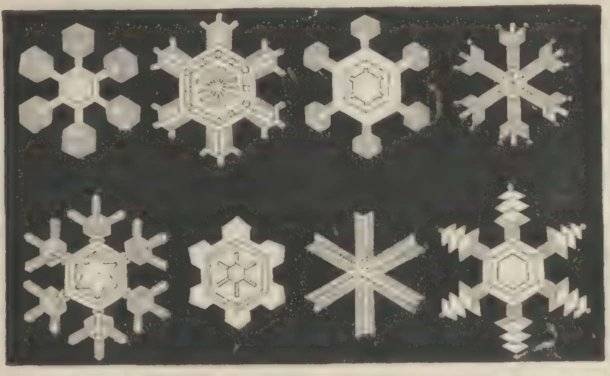


Fig. 723.

to that of an egg or an orange. The formation of hailstones has never been altogether satisfactorily accounted for; nor more especially their great size. On Volta's theory the hailstones are successively attracted by two clouds charged with opposite electricities; but if the hailstones were thus attracted, it is much more probable that the two clouds would be mutually attracted, and would unite.

863. **Ice. Regelation.**—Ice is nothing more than an aggregate of snow crystals, such as are shown in fig. 723. The transparency of ice is due to the close contact of these crystals, which causes the individual particles to blend into an unbroken mass, and renders the substance *optically*, as well as mechanically, continuous. When large masses of ice slowly melt away, a crystalline form is sometimes seen by the gradual disintegration into rude hexagonal prisms: a similar structure is frequently met with, but in greater perfection, in the ice caves or glaciers of cold regions.

A striking experiment of Tyndall has, however, more clearly revealed the beautiful structure of ice. When a piece of ice is cut parallel to its planes of freezing, and the radiation from any luminous source, as the sun, a glowing fire, a gas or oil flame, is permitted to pass through it, the disintegration of the substance proceeds in a remarkable way. By observing the plate of ice through a lens, numerous small crystals will be seen studding the interior of the block; as the heat continues these crystals expand, and finally assume the shape of six-rayed stars of exquisite beauty.

This is a kind of negative crystallisation, the crystals produced being composed of water, and owe their formation to the molecular disturbance caused by the absorption of heat from the source. Nothing is easier than to reproduce this phenomenon, if care be taken in cutting the ice. The planes of freezing can be found by noting the direction of the bubbles

in ice, which are either sparsely arranged in striæ at right angles to the surface, or thickly collected in beds parallel to the surface of the water. A warm and smooth metal plate should be used to level and reduce the ice to a slab not exceeding half an inch in thickness.

A still more important property of ice remains to be noticed. Faraday discovered that when two pieces of melting ice are pressed together they freeze into one at their points of contact. This curious phenomenon is now known under the name of *regelation*. The cause of it has been the subject of much controversy, but the simplest explanation seems to be that given by its discoverer. The particles on the exterior of a block of ice are held by cohesion on one side only; when the temperature is at 0° C., these exterior particles being partly free are the first to pass into the liquid state, and a film of water covers the solid. But the particles in the interior of the block are bounded on all sides by the solid ice, the force of cohesion is here a maximum, and hence the interior ice has no tendency to pass into a liquid even when the whole mass is at 0°. If the block be now split in halves, a liquid film instantly covers the fractured surfaces, for the force of cohesion on the broken surfaces has been lessened by the act. By placing the halves together, so that their original position shall be regained, the liquid films on the two fractured surfaces again become bounded by ice on both sides. The film being excessively thin, the force of cohesion is able to act across it: the consequence of this is, the liquid particles pass back into the solid state, and the block is reunited by *regelation*. Not only do ice and ice thus freeze together, but regelation also takes place between moist ice and any non-conducting solid body, as flannel or sawdust; a similar explanation to that just given has been applied here, substituting another solid for the ice on one side. It must be remarked, however, that many eminent philosophers dissent from the explanation we have given.

Whatever may be the true cause of regelation, there can be no doubt that this interesting observation of Faraday's explains many natural phenomena. For example, the formation of a snowball depends on the regelation of the snow granules composing it, and as regelation cannot take place at temperatures below 0° C., for then both snow and ice are dry, it is only possible to make a coherent snowball when the snow is melting.

The snow bridges, also, which span wide chasms in the Alps and elsewhere, and over which men can walk in safety, owe their existence to the regelation of gradually accumulating particles of snow.

864. **Glaciers.**—Tyndall has applied this regelating property of ice to the explanation of still grander phenomena—the formation and motion of glaciers, of which the following is a brief description. In elevated regions, what is termed the *snow line* marks the boundary of eternal snow, for above this the heat of summer is unable to melt the winter's snow. By the heat of the sun and the consequent percolation of water melted from the surface, the lower portions of the snow field are raised to 0° C.; at the same time this part is closely pressed together by the weight of the snow above, regelation therefore sets in, converting the loose snow into a coherent mass.

By increasing pressure the intermingled air which renders snow opaque becomes ejected and transparent ; ice then results. Its own gravity, and the pressure from behind, urges downwards the glacier, which has thus been formed. In its descent from the mountain the glacier behaves in all respects like a river, passing through narrow gorges with comparative velocity, and then spreading out and moving slowly as its bed widens. Further, just as the central portions of a river move faster than the sides, so Professor Forbes has ascertained, that the centre of a glacier moves quicker than its margin, and from the same reason (the difference in the friction encountered) the surface moves more rapidly than the bottom. To explain these facts, Forbes assumed ice to be a viscous body capable of flexion, and flowing like lava ; but as ice has not the properties of a viscous substance, the now generally accepted explanation of glacier motion is that supplied by the theory of regelation. According to this theory, the brittle ice of the glacier is crushed and broken in its passage through narrow channels, such as that of Trélaporte on Mont Blanc ; and then, as it emerges from the gorge which confined it, becomes reunited by virtue of regelation ; in this instance forming the well-known Mer de Glace. By numerous experiments Tyndall has established that regelation is adequate to furnish this explanation, and with complete success has artificially imitated, on a small scale, the moulding of glaciers by the crushing and subsequent regelation of ice.

LUMINOUS METEORS.

865. **Atmospheric electricity. Franklin's experiment.**—The most frequent luminous phenomena, and the most remarkable for their effects, are those produced by the free electricity in the atmosphere. The first physicists who observed the electric spark compared it to the gleam of lightning, and its crackling to the sound of thunder. But Franklin, by the aid of powerful electrical batteries, first established a complete parallel between lightning and electricity ; and he indicated, in a memoir published in 1749, the experiments necessary to attract electricity from the clouds by means of pointed rods. The experiment was tried by Dalibard in France ; and Franklin, pending the erection of a pointed rod on a spire in Philadelphia, had the happy idea of flying a kite, provided with a metallic point, which could reach the higher regions of the atmosphere. In June, 1752, during stormy weather, he flew the kite in a field near Philadelphia. The kite was flown with ordinary pack-thread, at the end of which Franklin attached a key, and to the key a silk cord, in order to insulate the apparatus ; he then fixed the silk cord to a tree, and having presented his hand to the key, at first he obtained no spark. He was beginning to despair of success, when, rain having fallen, the cord became a good conductor, and a spark passed. Franklin, in his letters, describes his emotion on witnessing the success of the experiment as being so great that he could not refrain from tears.

Franklin, who had discovered the power of points (575), but who did not understand its explanation, imagined that the kite withdrew from the

cloud its electricity; it is, in fact, a simple case of induction, and depends on the inductive action which the thunder-cloud exerts upon the kite and the cord.

866. **Apparatus to investigate the electricity of the atmosphere.**—The apparatus used to ascertain the presence of electricity in the atmosphere are: the electroscope, either with pith balls, straw, or gold leaf; the apparatus first used by Dalibard, and which consisted of an insulated iron rod, 36 yards in height; arrows discharged into the atmosphere, and even kites and captive balloons.

To observe the electricity in fine weather, when the tension is generally small, an electrometer is used, as devised by Saussure for this kind of investigation. It is an electroscope similar to that already described, but the rod to which the gold leaves are fixed is surmounted by a conductor 2 feet in length, and terminating either in a knob or a point (fig. 724). To protect the apparatus against rain, it is covered with a metallic shield 4 inches in diameter. The glass case is square, instead of being round, and a divided scale on its inside face indicates the divergence of the gold leaves or of the straws. This electrometer only gives signs of atmospheric electricity as long as it is raised in the atmosphere, so that it is in layers of air of which the electrical condition is superior to its own.

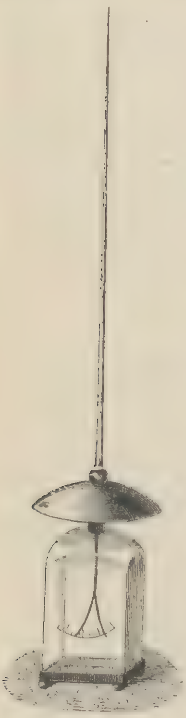


Fig. 724.

To ascertain the electricity of the atmosphere, Saussure also used a copper ball, which he projected vertically with his hand. This ball was fixed to one end of a metallic wire, the other end of which was attached to a ring, which could glide along the conductor of the electrometer. From the divergence of the straws, or of the gold leaves, the electrical condition of the air at the height which the ball attained could be determined. M. Becquerel, in experiments made on the St. Bernard, improved Saussure's apparatus, by substituting for the knob an arrow, which was projected into the atmosphere by means of a bow. A gilt silk thread, 88 yards long, was fixed with one end to the arrow, while the other was attached to the stem of an electroscope. Peltier used a gold-leaf electroscope, at the top of which was a somewhat large copper globe. Provided with this instrument, the observer stations himself in a commanding position—it is then quite sufficient to raise the electroscope even a foot or so to obtain signs of electricity.

To observe the electricity of clouds, where the tension is very considerable, use is made of a long bar terminating in a point. This bar, which is insulated with care, is fixed to the summit of a building, and its lower end is connected with an electrometer, or even an electric chimes

(fig. 545), which announces the presence of thunder-clouds. As, however, the bar can then give dangerous shocks, a metallic ball must be placed near it, which is well connected with the ground, and which is nearer the bar than the observer himself; so that if a discharge should ensue, it will strike the ball and not the observer. Professor Richmann, of St. Petersburg, was killed in an experiment of this kind, by a discharge which struck him on the forehead.

Sometimes also kites are used, provided with a point, and connected by means of a gilt cord with an electrometer. Captive ballons are also similarly used.

A good collector of atmospheric electricity consists of a fishing-rod with an insulated handle which projects from an upper window. At the summit is a bit of lighted amadou held in a metallic forceps, the smoke of which, being an excellent conductor, conveys the electricity of the air down a wire attached to the rod. A sponge moistened with alcohol, and set on fire, is also an excellent conductor.

867. **Ordinary electricity of the atmosphere.**—By means of the different apparatus which have been described, it has been found that the presence of electricity in the atmosphere is not confined to stormy weather, but that the atmosphere always contains free electricity, sometimes positive and sometimes negative. When the sky is cloudless, the electricity is always positive, but it varies in intensity with the height of the locality, and with the time of day. The intensity is greatest in the highest and most isolated places. No trace of positive electricity is found in houses, streets, or under trees; in towns positive electricity is most perceptible in large open spaces, on quays, or on bridges. In all cases, positive electricity is only found at a certain height above the ground. On flat land, it only becomes perceptible at a height of 5 feet; above that point it increases according to a law which is not made out, but which seems to depend on the hygrometric state of the air.

At sunrise the free positive electricity is feeble; it increases up to 8 to 11 o'clock, according to the season, and then attains its first maximum. It then decreases rapidly until a little before sunset, and then increases till it reaches its second maximum, a few hours after sunset; the remainder of the night the electricity decreases. These increasing and decreasing periods, which are observed all the year, are more perceptible when the sky is clearer, and the weather more settled. The positive electricity of fine weather is much stronger in winter than in summer.

When the sky is clouded, the electricity is sometimes positive and sometimes negative. It often happens that the electricity changes its sign several times in the course of the day, owing to the passage of an electrified cloud. During storms, and when it rains or snows, the atmosphere may be positively electrified one day, and negatively the next, and the numbers of the two sets of days are virtually equal.

The electricity of the ground has been found by Peltier to be always negative, but to different extents, according to the hygrometric state and temperature of the air.

868. **Causes of the atmospheric electricity.**—Many hypotheses have

been propounded to explain the origin of the atmospheric electricity. Some have ascribed it to the friction of the air against the ground, some to the vegetation of plants, or to the evaporation of water. Some, again, have compared the earth to a vast voltaic pile, and others to a thermo-electrical apparatus. Many of these causes may, in fact, concur in producing the phenomena.

Volta first showed that the evaporation of water produced electricity. Pouillet and others have subsequently shown that no electricity is produced by the evaporation of distilled water; but if an alkali or a salt is dissolved, even in small quantity, the vapour is positively and the solution is negatively electrified. The reverse is the case if the water contains acid. Hence it has been assumed that as the waters which exist on the surface of the earth and on the sea always contain salt dissolved, the vapours disengaged ought to be positively and the earth negatively electrified.

The development of electricity by evaporation may be observed by heating strongly a platinum dish, adding to it a small quantity of liquid, and placing it on the upper plate of the condensing electroscope (fig. 563), taking care to connect the lower plate with the ground. When the water of the capsule is evaporated, the connection with the ground is broken, and the upper plate raised. The gold leaves then diverge if the water contained salts, but remain quiescent if the water was pure.

Reasoning from this experiment, Pouillet has ascribed the development of electricity by evaporation to the separation of particles of water from the substances dissolved; but Reich and Reiss have shown that the electricity disengaged during evaporation could be attributed to the friction which the particles of water carried away in the current of vapour exercise against the sides of the vessel, just as in Armstrong's electrical machine. By a recent series of experiments, Gaugain has arrived at the same result; and thinks it no longer allowable to ascribe the atmospheric electricity to any changes that take place during the tranquil evaporation of sea water.

In support of the hypothesis which considers the earth as an immense source of voltaic electricity due to chemical actions, Becquerel has recently published numerous experiments to show that when land and water come in contact, electricity is always produced: the land taking a considerable excess of positive or negative electricity, and the water a corresponding excess of the opposite electricity, according to the nature of the salts or other compounds which the water held dissolved. This is a general fact which, according to M. Becquerel, is liable to no exception.

Becquerel experimented with an ordinary multiplier, the wire of which was connected with two platinum plates immersed in the pieces of ground, or the water whose electrical condition he wished to investigate. He thus found that when two moist pieces of ground are connected, that which contained the strongest solution took an excess of positive electricity. He found that in the neighbourhood of a river, even at some distance, the land and objects placed on the surface possessed an excess

of negative electricity, while the water and the aquatic plants which swam on the surface were charged with positive electricity. But according to the nature of the substances dissolved in the water, different effects were produced. As from Becquerel's experiments, the waters are sometimes positive and sometimes negative, and the earth in a contrary condition, it follows that water in evaporating must constantly send into the atmosphere an excess of positive or negative electricity, while the earth, by the vapours disengaged on its surface, allows an excess of the contrary electricity to escape. Now this excess of electricity ought necessarily to influence the distribution of the electricity in the atmosphere, and may serve to explain how it is that the clouds are sometimes positively and sometimes negatively electrified.

869. **Electricity of clouds.**—In general the clouds are all electrified, sometimes positively and sometimes negatively, and only differ in their greater or less tension. The formation of positive clouds is usually ascribed to the vapours which are disengaged from the ground, and condense in the higher regions. Negative clouds are supposed to result from fogs, which, by their contact with the ground, become charged with negative fluid, which they retain on rising into the atmosphere; or that, separated from the ground by layers of moist air, they have been negatively electrified by induction from the positive clouds, which have repelled into the ground positive electricity.

870. **Lightning.**—This, as is well known, is the dazzling light emitted by the electric spark when it shoots from clouds charged with electricity. In the lower regions of the atmosphere the light is white, but in the higher regions, where the air is more rarefied, it takes a violet tint; as does the spark of the electrical machine in a rarefied medium (617).

The flashes of lightning are sometimes several leagues in length; they generally pass through the atmosphere in a zigzag direction: a phenomenon ascribed to the resistance offered by the air condensed by the passage of a strong discharge. The spark then diverges from a right line, and takes the direction of least resistance. In vacuo electricity passes in a straight line.

Several kinds of lightning flashes may be distinguished—1. the zigzag flashes, which move with extreme velocity in the form of a line of fire with sharp outlines, and which entirely resemble the spark of an electrical machine; 2. the flashes, which, instead of being linear, like the preceding, fill the entire horizon without having any distinct shape. This kind, which is most frequent, appears to be produced in the cloud itself, and to illuminate the mass. Another kind is called *heat lightning*, because it illuminates the summer nights without the presence of any clouds above the horizon, and without producing any sound. The most probable of the many hypotheses which have been proposed to account for its origin, is that which supposes it to consist of ordinary lightning flashes, which strike across the clouds at such distances that the rolling of thunder cannot reach the ear of the observer. There are, further, the lightning flashes which appear in the form of globes of fire. These, which are sometimes visible for as much as ten seconds, descend from the clouds

to the earth with such slowness that the eye can follow them. They often rebound on reaching the ground; at other times they burst and explode with a noise like that of the report of many cannon.

The duration of the light of the first three kinds does not amount to a thousandth of a second, as has been determined by Mr. Wheatstone by means of a rotating wheel, which was turned so rapidly that the spokes were invisible: on illuminating it by the lightning flash, its duration was so short that whatever the velocity of rotation of the wheel, it appeared quite stationary; that is, its displacement is not perceptible during the the time the lightning exists.

871. **Thunder.**—The *thunder* is the violent report which succeeds lightning in stormy weather. The lightning and the thunder are always simultaneous, but an interval of several seconds is always observed between these two phenomena, which arises from the fact that sound only travels at the rate of about 1,100 feet in a second (162), while the passage of light is almost instantaneous. Hence an observer will only hear the noise of thunder five or six seconds, for instance, after the lightning, according as the distance of the thunder-cloud is five or six times 1,100 feet. The noise of thunder arises from the disturbance which the electric discharge produces in the air, and which may be witnessed in Kinnersley's thermometer. Near the place where the lightning strikes, the sound is dry and of short duration. At a greater distance a series of reports are heard in rapid succession. At a still greater distance the noise, feeble at the commencement, changes into a prolonged rolling sound of varying intensity. Some attribute the noise of the rolling of thunder to the reflection of sound from the ground and from the clouds. Others have considered the lightning not as a single discharge, but as a series of discharges, each of which gives rise to a particular sound. But as these partial discharges proceed from points at different distances, and from zones of unequal density, it follows not only that they reach the ear of the observer successively, but that they bring sounds of unequal density, which occasion the duration and inequality of the rolling. The phenomenon has finally been ascribed to the zigzags of lightning themselves, assuming that the air at each salient angle is at its greatest compression, which would produce the unequal intensity of the sound.

872. **Effects of lightning.**—The lightning discharge is the electric discharge which strikes between a thunder-cloud and the ground. The latter, by the induction from the electricity of the cloud, becomes charged with contrary electricity; and when the tendency of the two electricities to combine exceeds the resistance of the air, the spark passes, which is often expressed by saying that a thunder-bolt has fallen. Lightning in general strikes from above, but *ascending lightning* is also sometimes observed; probably this is the case when the clouds being negatively the earth is positively electrified, for all experiments show that at the ordinary pressure the positive fluid passes through the atmosphere more easily than negative electricity.

From the first law of electrical attraction, the discharge ought to fall first on the nearest and best-conducting objects, and, in fact, trees,

elevated buildings, metals, are more particularly struck by the discharge. Hence it is imprudent to stand under trees in stormy weather, especially if they are good conductors, such as oaks and elms. But the danger is said not to be the same under resinous trees, such as pines, for they conduct less well.

The effects of lightning are very varied, and of the same kind as those of batteries (616), but of far greater intensity. The lightning discharge kills men and animals, inflames combustible matters, melts metals, breaks bad conductors in pieces. When it penetrates the ground it melts the siliceous substance in its way, and thus produces in the direction of the discharge those remarkable vitrified tubes called *fulgurites*, some of which are as much as 12 yards in length. When it strikes bars of iron, it magnetises them, and often inverts the poles of compass needles.

After the passage of lightning, a highly peculiar odour is generally produced, like that perceived in a room in which an electrical machine is being worked. This odour was first attributed to the formation of an oxygenisd compound, to which the name *ozone* was given; but Schönbein, in 1840, has shown that ozone is a peculiar allotrophic modification of oxygen.

873. **Return shock.**—This is a violent and sometimes fatal shock which men and animals experience, even when at a great distance from the place where the lightning discharge passes. This is caused by the inductive action which the thunder-cloud exerts on bodies placed within the sphere of its activity. These bodies are then, like the ground, charged with the opposite electricity to that of the cloud; but when the latter is discharged by the recombination of its electricity with that of the ground, the induction ceases, and the bodies reverting rapidly from the electrical state to the neutral state, the concussion in question is produced, the *return shock*. A gradual decomposition and reunion of the electricity produces invisible effects; yet it appears that such disturbances of the electrical equilibrium are perceived by nervous persons.

The return shock is always less violent than the direct one; there is no instance of its having produced any inflammation, yet plenty of cases in which it has killed both men and animals; in such cases no broken limbs, wounds, or burns, are observed.

The return shock may be imitated by placing a frog near a strong electrical machine in action; at each spark taken from the machine, the frog experiences a smart shock.

874. **Lightning conductor.**—The ordinary form of this instrument is an iron rod, through which passes the electricity of the ground attracted by the opposite electricity of the thunder-clouds. It was invented by Franklin in 1755.

There are two principal parts in a lightning conductor; the rod and the conductor. The *rod* is a pointed bar of iron, fixed vertically to the roof of the edifice to be protected; it is from 6 to 10 feet in height, and its basal section is about 2 or 3 inches in diameter. The conductor is a bar of iron which descends from the bottom of the rod to the ground, which it penetrates to some distance. As, in consequence of their

rigidity, iron bars cannot always be well adapted to the exterior of buildings, they are best formed of wire cords, such as are used for rigging and for suspension bridges. In a report made by the Academy of Sciences on the construction of lightning conductors, the use of copper instead of iron wire in these conductors is recommended, inasmuch as copper is a better conductor than iron. The metallic section of the cords ought to be about ½ a square inch, and the individual wires 0·04 to 0·06 inch in diameter; they ought to be twisted in three strands, like an ordinary cord. The point of the lightning conductor ought to be of copper instead of platinum, for the sake of better conductivity. The conductor is usually led into a well, and to conduct it better with the soil it ends in two or three ramifications. If there is no well in the neighbourhood, a hole is dug in the soil to the depth of 6 or 7 yards, and the foot of the conductor having been introduced, the hole is filled with wood-ashes, which conduct very well and preserve the metal from oxidation.

The action of a lightning conductor depends on induction and the power of points (575); when a storm-cloud, positively electrified, for instance, rises in the atmosphere, it acts inductively on the earth, repels the positive and attracts the negative fluid, which accumulates in bodies placed on the surface of the soil, the more abundantly as these bodies are at a greater height. The tension is then greatest on the highest bodies, which are therefore most exposed to the electric discharge; but if these bodies are provided with metallic points, like the rods of conductors, the negative fluid, withdrawn from the soil by the influence of the cloud, flows into the atmosphere, and neutralises the positive fluid of the cloud. Hence, not only does a lightning conductor tend to prevent the accumulation of electricity on the surface of the earth, but it also tends to restore the clouds to their natural state, both which concur in preventing lightning discharges. The disengagement of electricity is, however, sometimes so abundant, that the lightning conductor is inadequate to discharge the ground, and the lightning strikes; but the conductor receives the discharge, in consequence of its greater conductivity, and the edifice is preserved.

Experiment has shown that, approximately, a lightning conductor protects a circular space around it, the radius of which is double its height. Thus, a building, 64 yards in length, would be preserved by two rods 8 yards in height, at a distance of 32 yards.

A conductor, to be efficient, ought to satisfy the following conditions: i. the rod ought to be so large as not to be melted if the discharge passes; ii. it ought to terminate in a point to give readier issue to the electricity disengaged from the ground, hence the rod is usually provided with a point of platinum or of gilt copper; iii. the conductor must be continuous from the point to the ground, and the connection between the rod and the ground must be as intimate as possible; iv. if the building which is provided with a lightning conductor contains metallic surfaces of any extent, such as zinc roofs, metal gutters, or iron work, these ought to be connected with the conductor. If the last two conditions are not fulfilled, there is great danger of *lateral discharges*; that is to say, that the

discharge takes place between the conductor and the edifice, and then it only increases the danger.

875. **Rainbow.**—The *rainbow* is a luminous meteor which appears in the clouds opposite the sun when they are resolved into rain. It consists of seven concentric arcs, presenting successively the colours of the solar spectrum. Sometimes only a single bow is perceived, but there are usually two; a lower one, the colours of which are very bright, and an external or *secondary* one, which is paler, and in which the order of the colours is reversed. In the interior rainbow the red is the highest colour; in the other rainbow the violet is. It is seldom that three bows are seen; theoretically a greater number may exist, but their colours are so feeble that they are not perceptible.

The phenomenon of the rainbow is produced by the decomposition of the white light of the sun when it passes into the drops and by its reflection from their inside face. In fact, the same phenomenon is witnessed in dewdrops and in jets of water; in short, wherever solar light passes into drops of water under a certain angle.

The appearance and the extent of the rainbow depend on the position of the observer, and on the height of the sun above the horizon; hence only some of the rays refracted by the rain-drops, and reflected in their concavity to the eye of the spectator, are adapted to produce the phenomenon. Those which do so are called *effective rays.*

To explain this let *n* (fig. 725) be a drop of water, into which a solar ray S*a* penetrates. At the point of incidence, *a*, part of the light is re-

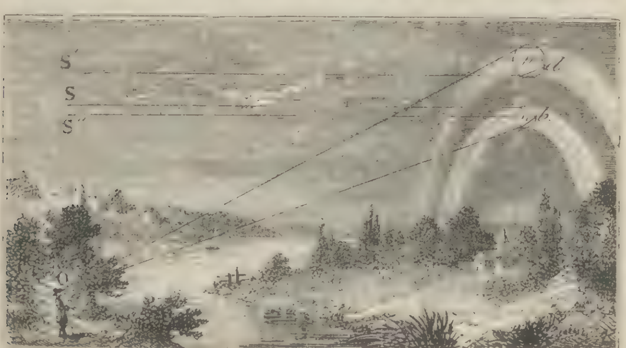


Fig. 725.

flected from the surface of the liquid; another, entering it, is decomposed and traverses the drop in the direction *ab*. Arrived at *b*, part of the light emerges from the rain-drop, the other part is reflected from the concave surface, and tends to emerge at *g*. At this point the light is again partially reflected, the remainder emerges in a direction *g*O, which forms with the incident ray, S*a*, an angle, called the *angle of deviation*. It is such rays as *g*O, proceeding from the side next the observer, which pro-

duce on the retina the sensation of colours, provided the light is sufficiently intense.

It can be shown mathematically that in the case of a series of rays which impinge on the same drop, and only undergo a reflection in the interior, the angle of deviation increases from the ray $S''n$, for which it is zero, up to a certain limit, beyond which it decreases, and that near this limit rays passing parallel into a drop of rain, also emerge parallel. From this parallelism a beam of light is produced sufficiently intense to impress the retina; these are the rays which emerge parallel and are efficient.

As the different colours which compose white light are unequally refrangible, the maximum angle of deviation is not the same for all. For red rays the angle of deviation corresponding to the active rays is 42° 2′, and for violet rays it is 40° 17′. Hence, for all drops placed so that rays proceeding from the sun to the drop make, with those proceeding from the drop to the eye, an angle of 42° 2′, this organ will receive the sensation of red light; this will be the case with all drops situated on the circumference of the base of a cone, the summit of which is the spectator's eye; the axis of this cone is parallel to the sun's rays, and the angle formed by the two opposed generating lines is 84° 4′. This explains the formation of the red band in the rainbow; the angle of the cone in the case of the violet band is 80° 34′.

The cones corresponding to each band have a common axis called the *visual axis*. As this right line is parallel to the rays of the sun, it follows that when this axis is on the horizon, the visual axis is itself horizontal, and the rainbow appears as a semicircle. If the sun rises, the visual axis sinks, and with it the rainbow. Lastly, when the sun is at a height of 42° 2′, the arc disappears entirely below the horizon. Hence, the phenomenon of the rainbow never takes place except in the morning and evening.

What has been said refers to the interior arc. The secondary bow is formed by rays which have undergone two reflections, as shown by the ray $S'i\,dfeO$, in the drop p. The angle $S'IO$ formed by the emergent and incident ray is called the angle of deviation. This angle is no longer susceptible of a maximum, but of a minimum, which varies for each kind of rays, and to which also efficient rays correspond. It is calculated that the minimum angle for violet rays is 54° 7′, and for red rays only 50° 57′: hence it is that the red bow is here on the inside, and the violet arc on the outside. There is a loss of light for every internal reflection in the drop of rain, and, therefore, the colours of the secondary bow are always feebler than those of the internal one. The secondary bow ceases to be visible when the sun is 54° above the horizon.

The moon sometimes produces rainbows like the sun, but they are very pale.

876. **Aurora borealis.**—The *aurora borealis*, or northern light, or more properly *polar aurora*, is a remarkable luminous phenomenon which is frequently seen in the atmosphere at the two terrestrial poles. The following is a description of an aurora borealis observed at Bossekop, in Lapland, lat. 70°, in the winter of 1838–1839.

In the evening, between 4 and 8 o'clock, the upper part of the fog which usually prevails to the north of Bossekop became coloured. This light became more regular, and formed an indistinct arc of a pale yellow, with its concave side turned towards the earth, while its summit was in the magnetic meridian.

Blackish rays soon separated the luminous parts of the arc. Luminous rays formed, becoming alternately rapidly and slowly longer and shorter, their lustre suddenly increasing and diminishing. The bottom of these rays always showed the brightest light, and formed a more or less regular arc. The length of the rays was very variable, but they always converged towards the same point of the horizon, which was in the prolongation of the north end of the dipping needle; sometimes the rays were prolonged as far as their point of meeting, and thus appeared like a fragment of an immense cupola.

The arc continued to rise in an undulatory motion towards the zenith. Sometimes one of its feet or even both left the horizon; the folds became more distinct and more numerous; the arc was now nothing more than a long band of rays convoluted in very graceful shapes, forming what is called the boreal crown. The lustre of the rays varied suddenly in intensity, and attained that of stars of the first magnitude; the rays darted

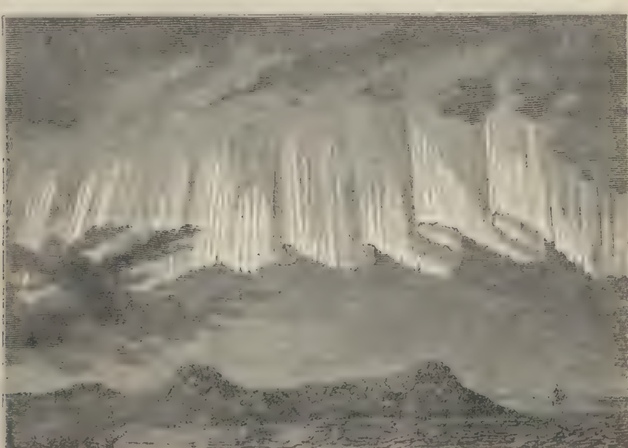


Fig. 726.

with rapidity, the curves formed and reformed like the folds of a serpent (fig. 726), the base was red, the middle green, while the remainder retained its bright yellow colour. Lastly, the lustre diminished, the colours disappeared: everything became feebler or suddenly went out.

A French scientific commission to the North observed 150 auroræ boreales in 200 days; it appears that at the poles, nights without an aurora borealis are quite exceptional, so that it may be assumed that they take place every night, though with varying intensity. They are visible at a

considerable distance from the poles, and over an immense area. Sometimes the same aurora borealis has been seen at the same time at Moscow, Warsaw, Rome, and Cadiz.

Numerous hypotheses have been devised to account for the auroræ boreales. The constant direction of their arc as regards the magnetic meridian, and their action on the magnetic needle (552), show that they ought to be attributed to electric currents in the higher regions of the atmosphere. This hypothesis is confirmed by the circumstance observed in France and other countries on August 29 and September 1, 1859, that two brilliant auroræ boreales acted powerfully on the wires of the electric telegraph; the alarums were for a long time violently rung, and despatches were frequently interrupted by the spontaneous abnormal working of the apparatus.

According to M. de la Rive the auroræ boreales are due to electric discharges which take place in polar regions between the positive electricity of the atmosphere and the negative electricity of the terrestrial globe; electricities which themselves are separated by the action of the sun, principally on the equatorial regions.

The occurrence of irregular currents of electricity which manifest themselves by abnormal disturbances of telegraphic communications is not infrequent; such currents have received the name of earth currents. Sabine has found that these magnetic disturbances are due to a peculiar action of the sun, and probably independently of its radiant heat and light. It has also been ascertained that the aurora borealis as well as earth currents invariably accompany these magnetic disturbances. According to Balfour Stewart auroræ and earth currents are to be regarded as secondary currents due to small but rapid changes in the earth's magnetism; he likens the body of the earth to the magnetic core of a Ruhmkorff's machine, the lower strata of the atmosphere forming the insulator, while the upper and rarer, and therefore electrically conducting strata, may be considered as the secondary coil.

On this analogy the sun may perhaps be likened to the primary current which performs the part of producing changes in the magnetic state of the core. Now in Ruhmkorff's machine the energy of the secondary current is derived from that of the primary current. Thus if the analogy be correct, the energy of the aurora borealis may in like manner come from the sun; but until we know more of the connection between the sun and terrestrial magnetism these ideas are to be accepted with some reserve.

CLIMATOLOGY.

877. **Mean temperature.**—The *mean daily temperature*, or simply *temperature*, is that obtained by adding together 24 hourly observations, and dividing by 24. A very close approximation to the mean temperature is obtained by taking the mean of the maxima and minima temperatures of the day and of the night, which are determined by means of the maximum and minimum thermometers. These ought to be protected from the solar rays, raised above the ground, and far from all objects which might influence them by their radiation.

The temperature of a month is the mean of those of 30 days, and the temperature of the year is the mean of those of 12 months. Finally, the temperature of a place is the mean of its annual temperature, for a great series of years. The mean temperature of London is 8·28° C., or 46·9° F. The temperatures in all cases are those of the air and not those of the ground.

878. **Causes which modify the temperature of the air.**—The principal causes which modify the temperature of the air are the latitude of a place, its height, the direction of the winds, and the proximity of seas.

Influence of the latitude. The influence of the latitude arises from the greater or less obliquity of the solar rays, for as the quantity of heat absorbed is greater the nearer the rays are to the normal incidence (308), the heat absorbed decreases from the equator to the poles, for the rays are then more oblique. This loss is however, in summer, in the temperate and arctic zones, partially compensated by the length of the days. Under the equator, where the length of the days is constant, the temperature is almost invariable ; in the latitude of London, and in more northerly countries, where the days are very unequal, the temperature varies greatly ; but in summer it sometimes rises almost as high as under the equator. The lowering of the temperature produced by the latitude is small ; thus in a latitude of 115 miles north of France, the temperature is only 1° C. lower.

Influence of altitude. The height of a place has a much more considerable influence on the temperature than its latitude. In the temperate zone a diminution of 1° C. corresponds in the mean to an ascent of 180 yards.

The cooling on ascending in the atmosphere has been observed in balloon ascents, and a proof of it is seen in the perpetual snows which cover the highest mountains. It is caused by the greater rarefaction of the air, which necessarily diminishes its absorbing power ; besides which the air is at a greater distance from the ground, which heats it by contact ; and finally there is the great diathermanous power of dry air.

The law of the diminution of temperature corresponding to a greater height in the atmosphere has not been made out, in consequence of the numerous perturbing causes which modify it, such as the prevalent winds, the hygrometric state, the time of day, &c. The difference between the temperature of two places at unequal heights is not proportional to the difference of level, but for moderate heights an approximation to the law may be made. As the mean of a series of very careful observations made by Mr. Walsh during balloon ascents, a diminution of 1° C. corresponded to an increase in height of 232 yards.

Direction of winds. As winds share the temperature of the countries which they have traversed, their direction exercises great influence on the air in any place. In Paris the hottest winds are the south, then come the south-east, the south-west, the west, the east, the north-west, north, and, lastly, the north-east, which is the coldest. The character of the wind changes with the seasons ; the east wind, which is cold in winter is hot in summer.

Proximity of the seas. The neighbourhood of the sea tends to raise the temperature of the air, and to render it uniform. The average temperature of the sea in equatorial and polar countries is always higher than that of the atmosphere. With reference to the uniformity of the temperature, it has been found that in temperate regions, that is, from 25° to 50° of latitude, the difference between the maximum and minimum temperature of a day does not exceed, on the sea, 2° to 3°; while upon the continent this amounts to 12° to 15°. In islands the uniformity of temperature is very perceptible, even during the greatest heats. In continents, on the contrary, the winters for the same latitudes become colder, and the difference between the temperature of summer and winter becomes greater.

879. **Gulf stream.**—A similar influence to that of the winds is exerted by currents of warm water. To one of these, the Gulf stream, the mildness of the climate in the north-west of Europe is mainly due. This great body of water, taking its origin in equatorial regions, flows through the Gulf of Mexico, from whence it derives its name; passing by the southern shores of North America it makes its way in a north-westerly direction across the Atlantic, and finally washes the coast of Ireland and the north-west of Europe generally. Its temperature in the Gulf is about 28° C. (and generally it is a little more than 5° C.) higher than the rest of the ocean on which it floats, owing to its lower specific gravity. To its influence is due the milder climate of west Europe as compared with that of the opposite coast of America; thus the river Hudson, in the latitude of Rome, is frozen over three months in the year. It also causes the polar regions to be separated from the coasts of Europe by a girdle of open sea; and thus the harbour of Hammerfest is open the year round. Besides its influence in thus moderating climate the Gulf stream is an important help to navigators.

880. **Isothermal lines.**—When on a map all the points whose temperature is known to be the same are joined, curves are obtained which Humboldt first noticed, and which he called *isothermal lines.* If the temperature of a place only varied with the obliquity of the sun's rays, that is, with the latitude, isothermal lines would all be parallel to the equator; but as the temperature is influenced by many local causes, especially by the height, the isothermal lines are always more or less curved. On the sea, however, they are almost parallel. A distinction is made between *isothermal lines*, *isotheral lines*, and *isochimenal lines*, where the mean *general*, the *mean summer*, and the *mean winter* temperatures are respectively constant. An *isothermal zone* is the space comprised between two isothermal lines. Kupffer also distinguishes *isogeothermic lines* where the mean temperature of the soil is constant.

881. **Climate.**—By the climate of a place is understood the whole of the meteorological conditions to which a place is subjected; its mean annual temperature, summer and winter temperatures, and by the extremes within which these are comprised. Some writers distinguish seven classes of climates, according to their mean annual temperature: a *hot climate* from 29° 5′ to 25° C.; a *warm climate* from 25° to 20° C.; a *mild climate* from

20° to 15°; a *temperate climate* from 15° to 10° C.; a *cold climate* from 10° to 5°; a *very cold climate* from 5° to zero; and an *arctic climate* where the temperate is below zero.

Those climates, again, are classed as *constant climates*, where the difference between the mean and summer and winter temperature does not exceed 6° to 8°; variable climates, where the difference amounts to from 16° to 20°; and extreme climates, where the difference is greater than 30°. The climates of Paris and London are variable; those of Pekin and New York are extreme. Island climates are generally little variable, as the temperature of the sea is constant; and hence the distinction between land and sea climates. Marine climates are characterised by the fact that the difference between the temperature of summer and winter is always less than in the case of continental climates. But the temperature is by no means the only character which influences climates; there are, in addition, the humidity of the air, the quantity and frequency of the rains, the number of storms, the direction and intensity of the winds, and the nature of the soil.

882. **Distribution of temperature on the surface of the globe.**—The temperature of the air on the surface of the globe decreases from the equator to the poles; but it is subject to perturbing causes so numerous and so purely local, that its decrease cannot be expressed by any law. It has hitherto not been possible to do more than obtain by numerous observations the mean temperature of each place, or the maximum and minimum temperatures. The following table gives a general idea of the distribution of heat in the northern hemisphere:

Mean temperatures at different latitudes.

Ayssinia	31·0° C.	Paris	10·8° C.
Calcutta	28·5	London	8·3
Jamaica	26·1	Brussels	10·2
Senegal	24·6	Strasburg	9.8
Rio de Janeiro	23·1	Geneva	9.7
Cairo	22·4	Boston	9·3
Constantine	17.2	Stockholm	5·6
Naples	16·7	Moscow	3·6
Mexico	16·6	St. Petersburg	3·5
Marseilles	14·1	St. Gothard	−1·0
Constantinople	13·7	Greenland	−7·7
Pekin	12·7	Melville Island	−18·7

These are mean temperatures. The highest temperature which has been observed on the surface of the globe is 47·4° at Esne, in Egypt, and the lowest is −56·7 at Fort Reliance, in North America; which gives a difference of 104·1° between the extreme temperatures observed on the surface of the globe.

The highest temperature observed at Paris was 38·4° on July 8, 1793, and the lowest −23·5 on December 26, 1798. The highest observed at Greenwich was 35° C. in 1808, and the lowest −20° C. in 1838.

No arctic voyagers have succeeded in reaching the poles, in consequence of these seas being completely frozen, and hence the temperature is not known. In our hemisphere the existence of a single *glacial pole*, that is, a place where there was the maximum cold, has been long assumed. But the bendings which the isothermal lines present in the northern hemisphere have shown that in this hemisphere there are two cold poles, one in Asia, to the north of Gulf Taymour, and the other in America, north of Barrow's Straits, about 15° from the earth's north pole. The mean temperature of the first of these poles has been estimated at −17°, and that of the second at −19°. With respect to the austral hemispheres, the observations are not sufficiently numerous to tell whether there are one or two poles of greatest cold, or to determine their position.

883. **Temperatures of lakes, seas, and springs.**—In the tropics the temperature of the sea is generally the same as that of the air; in polar regions the sea is always warmer than the atmosphere.

The temperature of the sea under the torrid zone is always about 26° to 27° at the surface; it diminishes as the depth increases, and in temperate as well as in tropical regions the temperature of the sea at great depths is between 2·5° and 3·5°. This temperature of the lower layers is caused by submarine currents which carry the cold water of the polar seas towards the equator.

The variations in the temperature of lakes are more considerable; their surface, which becomes frozen in winter, may become heated to 20° or 25° in summer. The temperature of the bottom, on the contrary, is virtually 4°, which is that of the maximum density of water.

Springs which arise from rain water which has penetrated into the crust of the globe to a greater or less depth necessarily tend to assume the temperature of the terrestrial layers which they traverse. Hence when they reach the surface their temperature depends on the depth which they have attained. If this depth is that of the layer of invariable temperature, the springs have a temperature of 10° or 11° in this country, for this is the temperature of this layer, or about the mean annual temperature. If the springs are not very copious their temperature is raised in summer and cooled in winter, by that of the layers which they traverse in passing from the invariable layer to the surface. But if they come from below the layer of invariable temperature, their temperature may considerably exceed the mean temperature of the place, and they are then called *thermal springs*. The following list gives the temperature of some of them:

Wildbad	37·5° C.
Vichy	40
Bath	46
Ems	56
Baden-Baden	67·5
Chaudes-Aigues	88
Trincheras	97
Great Geyser, in Iceland, at a depth of 66 ft.	124

From their high temperature they have the property of dissolving many mineral substances which they traverse in this passage, and hence form *mineral waters*. The temperature of mineral waters is not modified in general by the abundance of rain or of dryness ; but it is by earthquakes, after which they have sometimes been found to rise and at others to sink.

884. **Distribution of land and water.**—The distribution of water on the surface of the earth exercises great influence on climate. The area covered by water is considerably greater than that of the dry land ; and the distribution is unequal in the two hemispheres. The entire surface of the globe occupies about 200 millions of square miles, nearly $\frac{3}{4}$ of which is covered by water ; that is, the extent of the water is nearly three times as great as that of the land. The surface of the sea in the southern hemisphere is to that in the northern in about the ratio of 13 to 9.

The depth of the open sea is very variable, the lead generally reaches the bottom at about 300 to 450 yards ; in the ocean it is often 1,300 yards, and instances are known in which a bottom has not been reached at a depth of 4,500. It has been computed that the total mass of the water does not exceed that of a liquid layer surrounding the earth with a depth of about 1,100 yards.

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